ASPECTS OF THE CHEMISTRY OF REACTIVE INTERMEDIATES

by

JOHN BRENNAN, B. Sc. (Hons)

Thesis presented for the degree of

DOCTOR of PHILOSOPHY

University of Edinburgh

November 1976

Declaration

I declare that this thesis is of my own composition, that the work of which it is a record was carried out by myself, and that it has not been submitted in any previous application for a Higher Degree.

The thesis describes results of research carried out in the Department of Chemistry, University of Edinburgh under the supervision of Professor J. I. G. Cadogan since the 1st October 1973, the date of my admission as a research student.

The following courses have been attended: Recent Developments in the Theory of Concerted Processes, (five lectures), Dr. A. J. Bellamy; Industrial Research and Development, (5 lectures), Dr. B. Gravenor; Carbonium Ions (5 lectures), Professor B. Capon; High Speed Liquid Chromatography, (5 lectures), Professor J. H. Knox and Dr. J. Done; Molecular Rearrangements, (5 lectures), Dr. G. Tennant; Biomimetic Organic Chemistry, (5 lectures), Dr. R. M. Paton; Aspects of Nuclear Magnetic Resonance Spectroscopy, (6 lectures), Dr. R. K. Harris; Organic Phosphorus Compounds In General Synthesis, (5 lectures), Professor J. I. G. Cadogan and Dr. I. Gosney; Recent Advances in the Chemistry of β-Lactam Antibiotics, Chemical Society International Symposium, Cambridge, June 1976; Special Organic Chemistry Seminars, Edinburgh University Chemistry Department (3 years attendance).

Abstract

Investigations into the role of alkenes as promoters of benzyne formation from N-nitrosoacetanilide, using furan as a benzyne trap showed that the ability of the alkene to trap and efficiently delocalise free radicals involved in competing processes was of primary importance, while the resistance of the radical-alkene adduct to subsequent oxidation appeared to be an additional controlling factor. Thus good benzyne promotion was observed using dibenzofulvene and 1, 1-(bis-4-biphenylyl)-ethene while 1, 1-dibenzoylethene showed no promoting effect.

The use of 1, 1-diphenylethene as a promoter with ring-substituted N-nitrosoacetanilides showed that while yields of 4-t-butylbenzyne derived from N-nitroso-4-t-butylacetanilide were significantly increased with respect to the reaction in the absence of alkene, no significant effects were observed on the yields of arynes derived from N-nitroso-4-methoxyacetanilide and N-nitroso-4-methylacetanilide; the formation of free radical derived products was suppressed in each case.

N-Nitroso-2- and 4-chloroacetanilides in benzene and 1, 1-diphenylethene underwent substitution of chloride by acetate and formed diazonium chlorides. N-Nitroso-2- and 4-acetoxyacetanilides decomposed via the intermediacy of benzoquinone monodiazides and carbenes as was shown by the isolation of 1, 4-dioxa-2, 3-benzofulvalene from the decomposition of N-nitroso-2-acetoxyacetanilide in p-xylene. N-Nitroso-2-thioacetoxyacetanilide decomposed in benzene to yield 1, 2, 3-benzothiadiazole.

In the reaction of diaroyl peroxides with dimethyl acetylene-dicarboxylate (DMAD) to form tetramethyl naphthalen-1, 2, 3, 4-tetracarboxylates low yields were shown, by measurement of carbon dioxide evolution, to be in part due to inefficient decarboxylation of the aroyloxy radicals; aroic acid formation was insignificant. The decomposition of dicinnamoyl peroxide in DMAD gave no cyclised product while bis-α-methylcinnamoyl peroxide in DMAD gave a low yield of dimethyl 3-methylnaphthalen-1, 2-dicarboxylate.

Reports on some aspects of this work have been published:-

"Aromatic Annelation by Reaction of Aryl Radicals with Dimethyl Acetylenedicarboxylate and Related Compounds," by Brian D. Baigrie, John Brennan, J. I. G. Cadogan, John Cook, and John T. Sharp, J. Chem. Soc., Perkin I, 1975, 1060.

"Novel Reactions of Diazonium Salts; Direct Conversion of o- and p-Chlorobenzenediazonium Acetates into Hydroxybenzenediazonium Salts of o-Acetoxybenzenediazonium Acetate into the Carbene, 2-Oxocyclohexa-3, 5-dienylidene and of o-Thioacetoxybenzenediazonium Acetate into 1, 2, 3-Benzothiodiazole," by John Brennan, J. I. G. Cadogan, and John T. Sharp, J. C. S. Chem. Comm., 1976, 850.

Acknowledgements

I would like to thank Professor J. I. G. Cadogan for suggesting the topic of research, and to thank Professor Cadogan and Dr. J. T. Sharp for their assistance, advice and encouragement while the research was being undertaken.

My thanks are also extended to the following members of Edinburgh University Chemistry Department: to Mr. Tom Naisby for technical assistance; to Mr. David Thomas for instruction in the use of the MS-902 mass spectrometer; to Mrs. C. G. Ranken for her patience and co-operation in the typing of the manuscript; to all other members of the technical and academic staffs who have supplied back-up services or offered practical advice and assistance.

Finally I would like to acknowledge financial support from the Science Research Council, for the three years during which this research was carried out.

GENERAL CONTENTS

INTRODUCTION CONTENTS

Introduction

The research which will be described concerned the mechanism and synthetic aspects of the chemistry of acylarylnitrosamines, and of reactions developed from this study. Of specific interest were reactions involving free radicals and arynes, reactive intermediates known to be present during the thermal decomposition of acylarylnitrosamines.

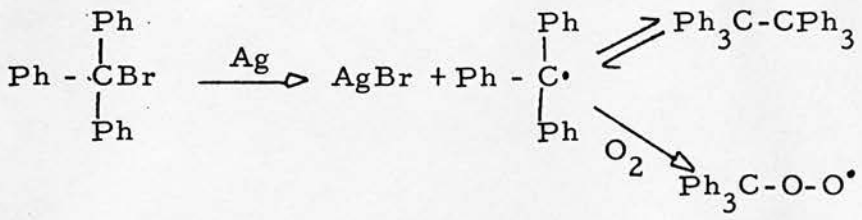
In order to set these studies in perspective the general chemistry of free radicals and arynes will be discussed briefly. A more detailed discussion of the chemistry of acylarylnitrosamines will be undertaken, necessitated by a century of research into these compounds during which the development and abandonment of many theories has taken place; this has resulted in an almost complete understanding of many of the complex mechanisms involved in the behaviour of these compounds.

The reaction of aryl radicals with alkynes to form cyclised products, which was discovered during research into the chemistry of acylarylnitrosamines, and developed using diaroyl peroxides as the source of aryl radicals, will be discussed separately.

Free Radicals

Historical Introduction

Free radicals are species possessing one or more unpaired electrons. The presence of free radicals in a chemical reaction was first recognised by Gomberg[1] in 1900 when he proposed that the reaction of triphenylmethyl halides with silver or zinc produced triphenylmethyl radicals; these he proposed reacted reversibly with each other (dimerised) or reacted with atmospheric oxygen if present. The former proposal was subsequently shown to be incorrect.



The generation of methyl radicals at low pressure and high temperature from tetramethyl lead by Paneth and Hofeditz[2] in 1929, and the measurement of their half lives under these conditions furnished further evidence for the existence of radical intermediates.

It was not however until 1934 when Grieve and Hey[3] suggested that aryl free radicals were generated from acylarylnitrosamines under mild conditions in organic solvents that a major revival of interest in these species was stimulated. This revival was further promoted by the work of Kharasch and Mayo[4] between 1933 and 1937 on the addition of hydrogen bromide to terminal alkenes, from which it was concluded[4, 5] that the addition could, and did take place by two separate mechanisms; one was a normal ionic Markownikov mechanism and the other a light or peroxide induced free radical anti-Markownikov mechanism.

Within a few years the accumulation of experimental data was such that the role of free radicals as intermediates in a vast number of diverse organic reactions was established beyond doubt, these are now known to extend from the photolytic degradation of simple alkyl halides to the free radical chain processes involved in the industrial

production of polymers.

The mechanisms of such reactions have been intensively studied and there now exists a vast literature on free radical chemistry as well as many excellent reviews.[5,6]

The Generation of Free Radicals

The most direct method for the generation of free radicals is the homolytic fission of a covalent bond; this can be achieved thermally or photolytically and for the production of a specific radical a specific bond must be selectively cleaved.

The above requirements are met by diacyl and diaroyl peroxides which in many cases decompose smoothly in solution below 100°. The general scheme for such decompositions is:-

$$R\cdot C(=O) - O - O - C(=O) - R \longrightarrow 2R - C(=O) - O^{\cdot} \longrightarrow 2R^{\cdot} + 2CO_2$$

In the above case R may be alkyl vinyl, styryl or aryl, but in many cases the decomposition is far more complex as has been shown by De Tar.[7]

The energy necessary to cleave the O-O bond in gaseous diacetyl peroxide is 124kJmol^{-1} [8] and in dibenzoyl peroxide is 130kJmol^{-1};[9] both decompose smoothly in chlorobenzene at 40° with first order rate constants of 2.2×10^{-7} sec^{-1} and 0.7×10^{-7} sec^{-1} respectively.[10]

Similarly other routes which give rise to acyloxy or aroyloxy radicals may be used to generate the parent alkyl or aryl radical. Some examples of these are the thermolyses of lead tetraacetate,[11] lead tetrabenzoate[12] and phenyliodosobenzoate,[13] and the electrolyses of alkanoates[14,15] (the Kolbe reaction) and benzoates.[16]

The use of reactions which give aryl radicals by the extrusion of carbon dioxide from aroyloxy radicals are to some degree limited in their application. While acetoxy radicals have an activation energy for decarboxylation of 27.5 kJ mol^{-1} [17] and do so exothermically with an enthalpy of -66kJ mol^{-1},[9] benzoyloxy radicals have an activation

energy for decarboxylation of 58kJ mol[18] and the enthalpy for the process is approximately zero.[9] Acetoxy radicals produce methyl radicals at the diffusion controlled rate for decarboxylation[17] while benzoyloxy radicals decarboxylate 5×10^5 times more slowly,[17, 18] allowing them time to interact with the reaction medium. Thus while attempts to trap the acetoxy radical have failed[19] when dibenzoyl peroxide is decomposed in benzene at 80° (0.05 M solution) benzoic acid (20 m/100 m peroxide) derived from benzoyloxy radicals can be identified,[20] in xylene under the same conditions benzoic acid is produced as 82 m/100m peroxide[21] and in styrene it is estimated that the benzoyloxy radical is incorporated as over 190 m/100 m peroxide in the resulting polymer.[18]

The extrusion of nitrogen from azo compounds can be utilised in the formation of radicals. Thermolysis of diarylazo compounds is not generally considered to be a useful source of aryl radicals due to the high stability conferred upon them by conjugation through the azo function (Ph·N:N·Ph is stable above 700°).[22] Where such conjugation is absent radicals can be readily generated.

Phenylazotriphenylmethane has been used as a source of phenyl and triphenylmethyl radicals.[23, 24]

$$Ph_3C\text{-}N{=}N\text{-}Ph \longrightarrow Ph_3C^{\bullet} + Ph^{\bullet} + N_2$$

The compound is normally decomposed thermally and the reaction is thought to proceed synchronously;[24] a large number of arylazoalkyl and dialkylazo compounds have been shown to behave similarly.[25]

1, 3-Diaryltriazines[26] will, when heated to 160°, extrude nitrogen to yield aryl and anilino radicals while if these compounds are nitrosated at room temperature with nitric oxide[27] or at low temperatures with nitrosyl chloride[28] and decomposed in benzene biaryls are obtained; it was shown[28] that the aryl radicals were derived from both aryl groups on the triazine, probably via the bis-diazoether:-

$$Ar\text{-}N{=}N\text{-}O\text{-}N{=}N\text{-}Ar$$

Biaryls from these triazines are most conveniently obtained in

good yield by nitrosating the triazine in boiling benzene with amyl nitrite.[29]

Nitrosation of aromatic amines with alkyl nitrites has been used as a source of aryl radicals for the formation of biaryls[30] and as a means of deaminating aromatic amines, using tetrahydrofuran as a hydrogen donor.[31] The mechanism of this nitrosation has not been closely studied although the formation of an aryldiazohydroxide is probably an initial step.

$$Ar\,NH_2 + RONO \longrightarrow ROH + Ar{\cdot}NH{\cdot}NO \longrightarrow Ar\text{-}N{=}N\text{-}OH \rightsquigarrow Ar^{\bullet}$$

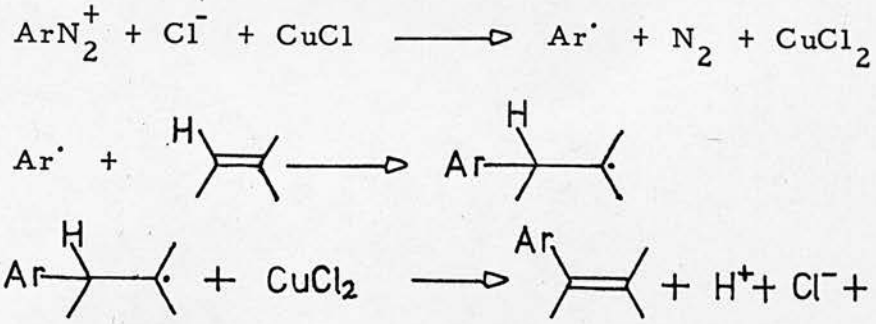
The classical method for generating free radicals from arylamines is by the formation and decomposition of aryldiazonium salts; the one electron oxidation of the aryldiazonium ion to the corresponding radical which loses nitrogen gives rise to the desired radical.

$$Ph\,NH_2 \longrightarrow Ph\,N_2^+X^- \xrightarrow{e^-} X^{\cdot} + Ph\,N_2^{\cdot} \longrightarrow Ph^{\cdot} + N_2$$

Probably the best known example is the Gomberg reaction[32] in which a mixture of an aqueous solution of an aryldiazonium salt and benzene is treated with sodium hydroxide to give biaryls. Although direct evidence for precise mechanistic detail is scarce Hey[33] showed the reaction to be radical in nature and it probably proceeds <u>via</u> the diazotate anion.

$$Ph{\cdot}N{:}N{\cdot}O^-$$

Evidence in support of this comes by analogy with a detailed study of the decomposition of acylarylnitrosamines in benzene undertaken by Rüchardt.[34] Evidence for the catalytic redox nature of these diazonium salt reactions has been presented in a kinetic study of the Meerwein arylation reaction.[35]

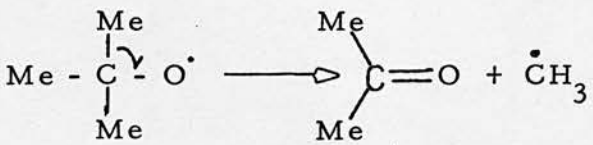


Photolysis of azo compounds,[36] diacylperoxides[37] and dialkyl peroxides[38] may be used as a means of generating alkyl and aryl radicals by mechanisms similar to those in thermolysis. Also iodobenzene, diphenyl mercury tetraphenyl lead,[39] triphenylarsine and tetraphenylstannane[40] will all yield phenyl radicals upon photolysis.

Free Radical Reactions

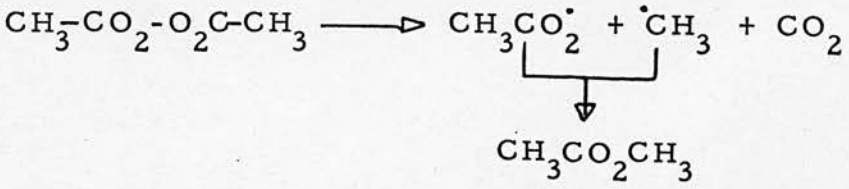
Free radicals may undergo fragmentation, addition, substitution, rearrangement, or combinations of these basic reactions.

Fragmentations of acyloxy and aroyloxy radicals have already been discussed in the section on peroxides (p. 3). Alkoxy radicals can also undergo fragmentation, usually with the extrusion of an aldehyde or ketone and a reactive alkyl radical; an example of this is the fragmentation of the t-butoxy radical at 200°.[41]



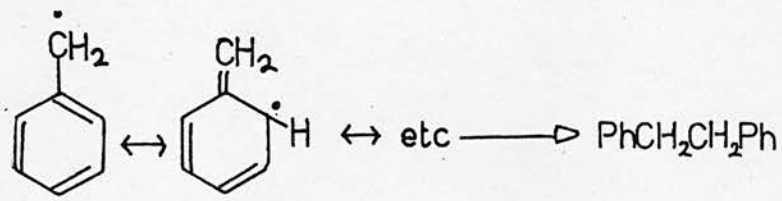
The arylazo radical $ArN_2^{\cdot}$ is very unstable although evidence exists for its recombination with precursors under cage conditions, indicating that the radical has a discrete existence prior to fragmentation.[42]

The simplest addition reaction of a free radical is that with another radical to produce a neutral product, an example of this is the solvent cage addition of methyl and acetoxy radicals to give methyl acetate.

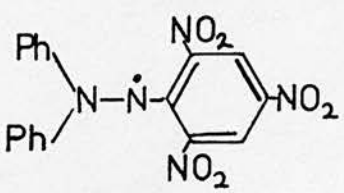


This product also furnished evidence for the step-wise decomposition of diacetyl peroxide.[43]

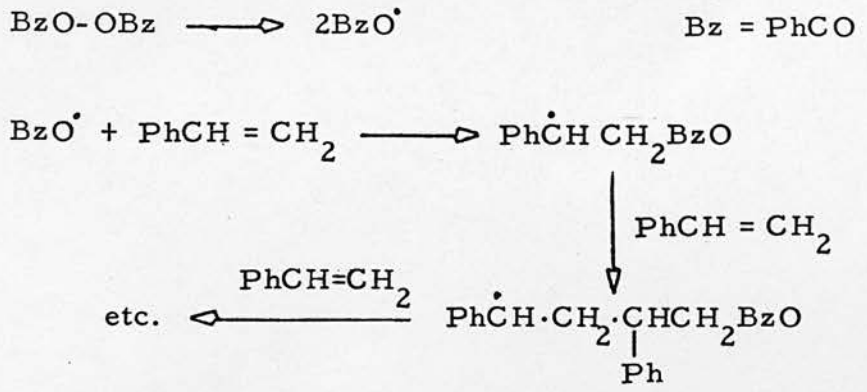
Radical-radical additions need not be fast solvent cage processes; the benzyl radical has a delocalised radical centre and will normally persist in solution until it dimerises with another benzyl radical to yield 1, 2-diphenylethane.[44]



This persistence of certain radicals, which may be by delocalisation or steric hindrance is used to produce radical scavangers; these are persistent radicals which may be unreactive in the solid state for many years and yet are sufficiently reactive in solution to undergo radical-radical additions with contaminant radical species. Diphenylpicrylhydrazyl is an example of such a scavanger.[45]

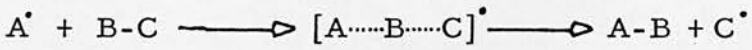


Addition of a free radical to a non-radical species will inevitably result in the formation of a further radical; additions of this kind must therefore be followed by a further reaction of the newly formed radical. If the newly formed species merely adds to a further molecule, the product of which adds in turn to another then a polymer will result; an example of this is the dibenzoyl peroxide initiated polymerisation of styrene.[18]

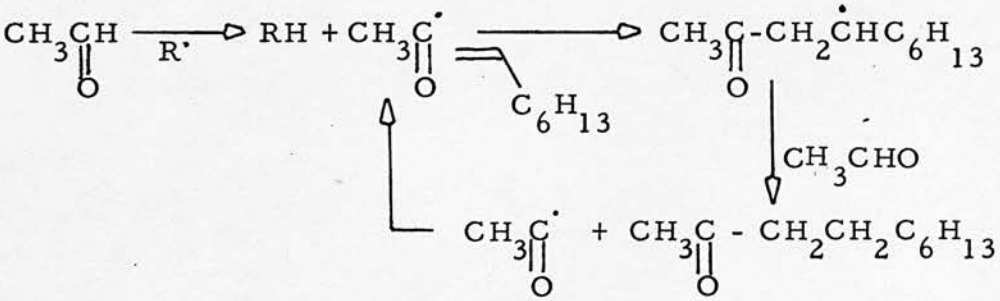


Such a radical chain process may be terminated by radical-radical addition, disproportionation or substitution (see below).

If the addition process described above could be terminated after one addition then a small molecule could be formed. A simple method of forming such a small molecule is by abstraction of an atom by the radical adduct; abstraction is homolytic substitution of the type:-



The formation of alkyl ketones from aldehydes and alkenes is a radical addition-abstraction process.[46]

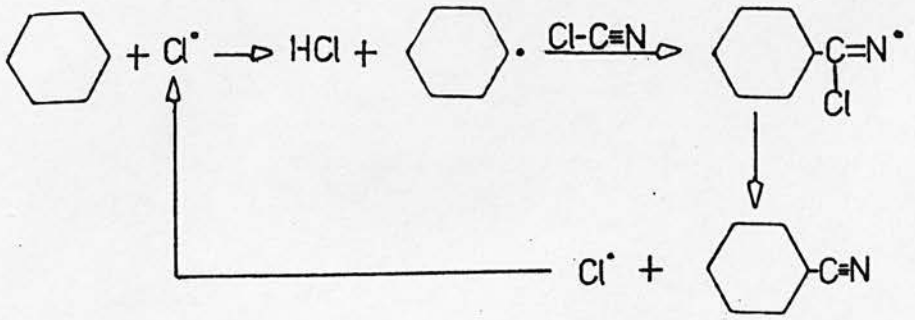


R· = free radical initiator

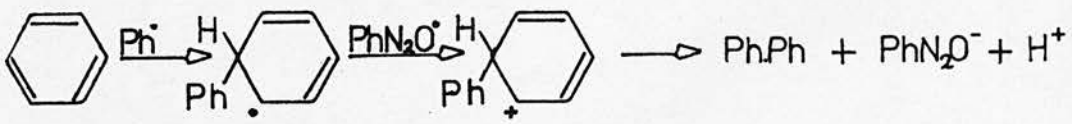
The light or peroxide induced anti-Markownikov addition of hydrogen bromide to terminal alkenes observed by Kharasch and Mayo[4] was probably the first studied example of such a radical addition-abstraction process.

Another commonly observed radical substitution process is addition-elimination.

Most simply this will involve an intermediate radical species which decomposes non-reversibly to extrude a small molecule and a radical; this is proposed in the radical induced reaction of cyanogen chloride and cyclohexane.[47]



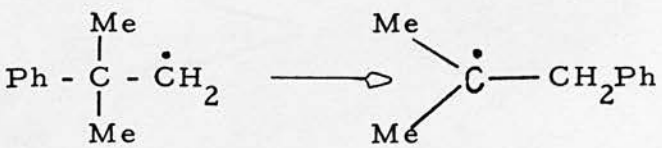
More commonly the intermediate radical species is oxidised to a cation which may eliminate an atom in the β position to the radical, usually hydrogen. Such an elimination has been suggested as a key step in the Gomberg biaryl synthesis.[34]



The Meerwein reaction (p. 5) has also been shown to proceed via this type of mechanism, utilising Cu(II)→Cu(I) as the oxidising process.

Radical rearrangements have been less extensively reported than those involving carbonium ions; they both however have the same basis, that the rearrangement should be to give a more stable species; similarly the order of stability is $3^{o} > 2^{o} > 1^{o}$.

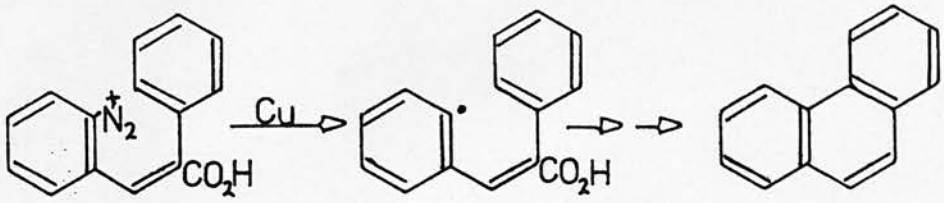
The first rearrangement to be observed and studied was that of the neophyl radical.[48]



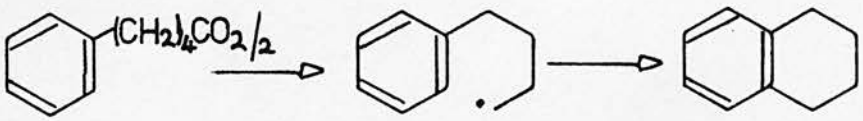
Free radical rearrangement reactions have recently been reviewed.[6(c)]

Cyclisation onto an Aromatic Nucleus Using Carbon-Centred Free Radicals.

The classical reaction of this type is that developed by Pschorr for phenanthrene synthesis by the diazotisation of 2-amino-α-phenyl-cinnamic acid followed by copper-powder reduction of the diazonium compound.[49]

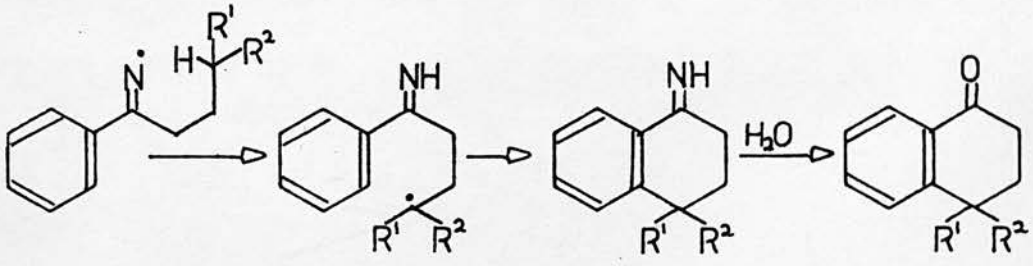


De Tar has shown that the 4-phenylbut-1-yl radical derived from bis-(4-phenylbutanoyl) peroxide will cyclise into the aromatic nucleus to form tetralin (56 m/100 m peroxide).[50]



The main competing reaction is dimerisation of the alkyl radicals (32 m dimer/100 m peroxide).

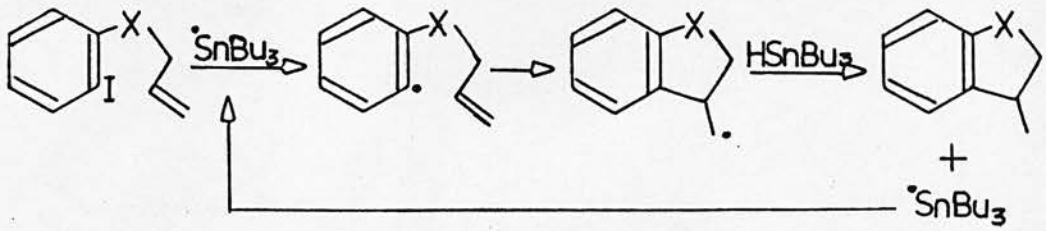
Forrester has recently observed the similar formation of cyclic aromatic ketones via intramolecular hydrogen abstraction by the iminyl radical.



The iminyl radical was derived from the persulphate oxidation of the corresponding oximinoacetic acid and the highest yield (73%) was

obtained when $R^1=R^2=Me$ and the lowest (32%) when $R^1=R^2=H$; the major competing reaction was hydrogen abstraction by the alkyl radical.[51]

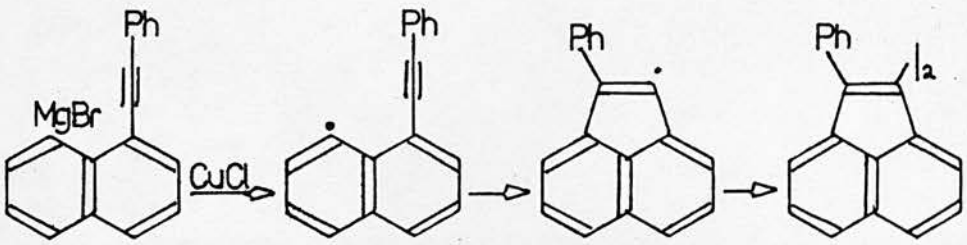
Addition of an aryl radical to an intramolecular double bond has been used by Beckwith in the synthesis of 3-methyl-2,3-dihydrobenzofuran and 1-methylindan.[52]



X= O, 99% product
CH_2, 80%

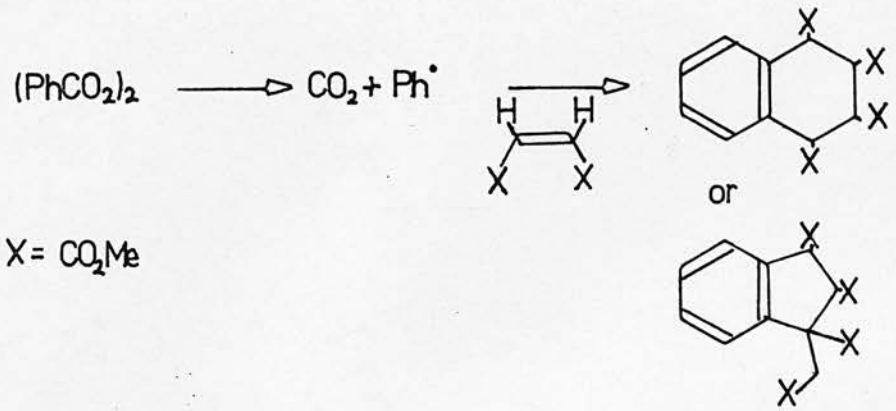
The exclusive formation of five-membered rings was attributed to the steric requirements of the transition state.[53]

Intramolecular radical addition to a triple bond has been suggested in the reaction of 8-phenylethynylnaphthalen-1-magnesium bromide with cuprous chloride.[54]



Intermolecular reactions of carbon radicals involving cyclisation are very scarce and only two have been reported in the literature. De Tar observed that when dibenzoyl peroxide was thermally decomposed in dimethyl maleate two stereoisomeric cyclisation products were formed;[55] he was however unable to assign to the stereoisomers a

definite structure from the two possible structures, one an indan derivative and one a tetralin derivative. The yield was 50 m/100 m peroxide.

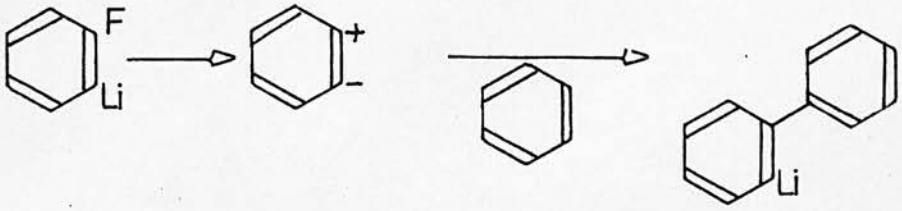


The reaction of dimethylacetylenedicarboxylate with aryl radicals has also been reported[56] and is discussed separately.

Benzyne

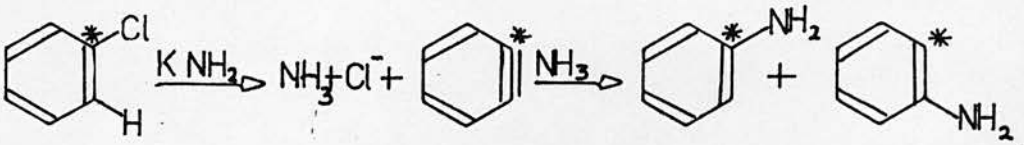
Historical Introduction

The existence of 1, 2-didehydrobenzene, or benzyne, was not seriously considered until 1942 when Wittig[57] suggested that in benzene 2-fluorophenyl lithium was decomposing via a 1, 2-dipolar intermediate.



Wittig was subsequently to be shown correct in the suggestion that 1, 2-didehydrobenzene was an intermediate although the 1, 2-dipolar hypothesis was to be discarded in favour of an uncharged structure in which both positions were equivalent and connected by a formal covalent bond.

The classical experiment in showing this equivalence was carried out by Roberts[58] when he reacted 1-^{14}C chlorobenzene with potassium amide in liquid ammonia to obtain aniline; chemical degradation of this product showed that 50% of the amino function had been on a ^{14}C labelled position whilst the remaining 50% had been evenly distributed on the two possible ortho positions. Roberts concluded that an electrically neutral symmetrical intermediate had been generated and that benzyne could be that intermediate.



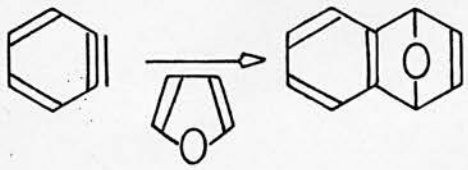
* ^{14}C label

This discovery helped to rationalise many observations of abnormal rearrangements which occurred when aryl halides were reacted with amide

in liquid ammonia.[59]

Further evidence for the existence of 1, 2-didehydroaromatics was produced by Huisgen and Rist[60] who showed that base treatment of 1- and 2-fluoronaphthalene generated a common intermediate which gave the same addition product ratios.

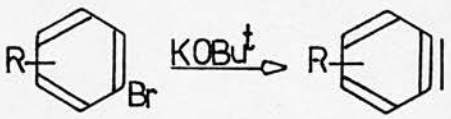
Shortly afterwards Wittig showed that the reactive 'third bond' of benzyne could be trapped by furan in a Diels-Alder reaction to yield 1,4-dihydronaphthalen-1,4-endoxide.[61]



The Generation of Benzyne

The liquid ammonia-amide system used by Roberts[58] had the disadvantage that the benzyne generated could easily react with the ammonia solvent and thus compete with any reactants in the system which were required to react with the benzyne.

A system which overcame this drawback was the treatment of an aryl halide in an inert solvent with potassium t-butoxide.[62]



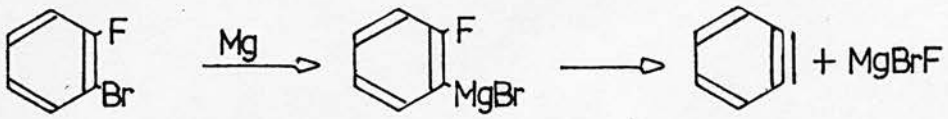
Here again the benzyne was generated by base abstraction of a proton ortho to a halide to give an ortho haloaryl anion which expelled the halide ion to yield an aryne.

Attack by base ortho to leaving groups other than halogen has been observed to yield benzyne.

Y may be phenoxy,[63] trialkylammonium,[64] diarylsulphonium,[65] phenyliodonium[66] and diazonium;[67] with the exception of aryldiazonium acetates which will be discussed separately none of these has proved to be a particularly useful source of arynes.

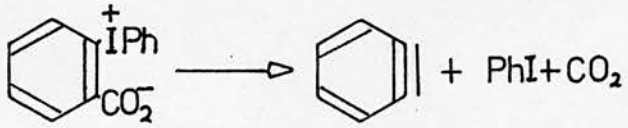
Methods for generating an anion ortho to a leaving group, other than by base abstraction of an ortho proton, have generally proved to be of greater synthetic utility.

Wittig found that 1, 2-bromofluorobenzene in ether would react at the bromide function with lithium amalgam to give 2-fluorophenyl lithium, which at normal temperatures would decompose to lithium fluoride and benzyne.[61] Similarly 1, 2-bromofluorobenzene would react with magnesium in tetrahydrofuran to give 2-fluorophenylmagnesium bromide which at normal temperatures would spontaneously decompose to benzyne and magnesium salts.[61]

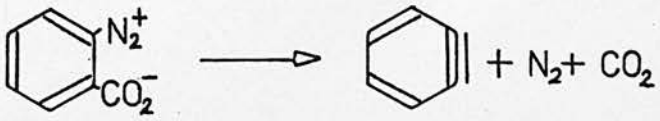


Decarboxylation of the 2-halophenylcarboxylate salts of certain metals will give benzyne upon the subsequent elimination of halide.[68]

Carboxylate ortho to leaving groups other than halide has also been used as a source of benzyne; diphenyliodonium carboxylate when thermolysed at 160° will yield benzyne in up to 70% yield.[69]



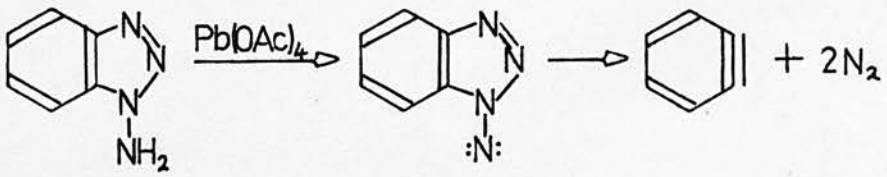
Perhaps the most commonly used source of benzyne is benzene-diazonium-2-carboxylate which decomposes to benzyne under mild conditions in organic solvents.[70]



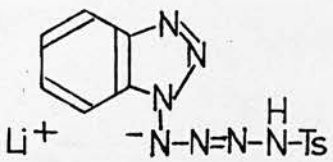
The solid zwitterionic salt is extremely hazardous to handle[71] but it can be conveniently generated in situ by diazotisation of anthranilic acid with alkyl nitrites.[72]

The extrusion of stable molecules from unstable fused bicyclic benzo compounds has been widely utilised to generate benzyne.

One of the earliest reactions of this type was the decomposition of 1, 2, 3-benzothiadiazole-1, 1-dioxide which fragmented at 20° in organic solvents to yield benzyne sulphur dioxide and nitrogen.[73] Rees developed similar bicyclic systems; the lead tetraacetate oxidation of 1-aminobenzotriazole gives benzyne in high yield and is thought to proceed via a nitrene intermediate.[74]



The reaction proceeds at room temperature but has the disadvantage that any system in which the reaction is used must be stable to lead tetraacetate. In an attempt to overcome this drawback Rees synthesised the lithium salt of 1-(benzotriazo-1-yl)-4-(p-tolyl-sulphonyl)tetrazene.[75]



This compound spontaneously decomposes to benzyne upon dissolution in tetrahydrofuran; the decomposition also probably proceeds

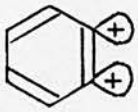
via 1-nitrenobenzotriazole.

Benzyne has also been generated photolytically, generally from compounds which do not produce benzyne thermally.

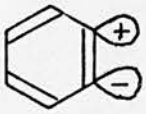
By analogy with the photochemical generation of phenyl radicals from iodobenzene, photolysis of 1, 2-diiodobenzene yields benzyne and iodine;[76] 2-iodophenylmercuric iodide upon photolysis similarly yields benzyne.[77] Phthaloyl peroxide decomposes thermally by a step-wise radical, non-benzyne, mechanism but is photolysed to yield two molecules of carbon dioxide and benzyne;[77] this has been used to observe the i.r. spectrum of matrix isolated benzyne at 8K.[78] Also used for this purpose have been benzocyclobutadione[78] and 3-diazobenzofuranone;[79] photolysis of the latter compound allowed the observation of a benzyne C≡C stretch as well as the previously observed C-C and C=C stretches.[79]

The Structure, Reactivity and Reactions of Benzyne

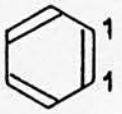
As would be expected for a structure in which a triple bond is represented as being in a six membered ring, benzyne is a highly reactive intermediate. Both experimental[80] and theoretical[81] (MINDO/3) calculations estimate a heat of formation from benzene of 494 ± 20 kJ mol^{-1}. The 'triple bond' can be more realistically seen as two adjacent distorted sp^2 orbitals, each containing one electron; these may be symmetrical and antisymmetrical singlet or diradical triplet.



S



A



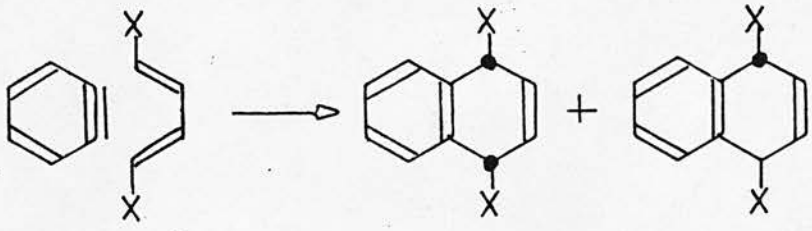
T

Although triplet benzyne has been suggested as an intermediate,[74] and an unsuccessful attempt has been made to photochemically generate this intermediate,[83] it is generally accepted that benzyne exists as a singlet. This assumption is based on several theoretical approaches,[84, 85] the most recent being Dewar's MINDO/3[81] which suggests a singlet-

triplet separation of 30-40 kJ mol^{-1}.

Hoffmann's prediction that benzyne should be more stable in the symmetrical singlet state by 147kJ mol^{-1} [85] may be tested experimentally since the Woodward Hoffmann rules[86] predict that a [2+4] thermal addition of symmetrical singlet benzyne would be a concerted process while a [2+2] thermal addition would be non-concerted.

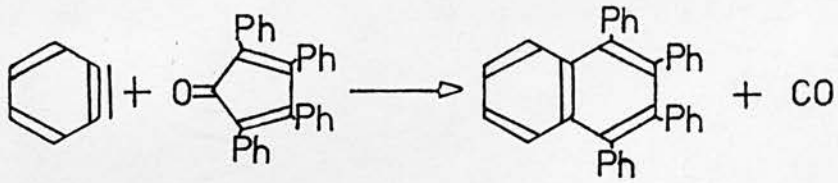
Jones[87] showed that benzyne added to trans-trans-dimethylbuta-1, 3-diene-1, 4-dicarboxylate to give the cis dihydronaphthalene diester exclusively, suggesting concerted addition.



X=CO_2Me 100% 0%

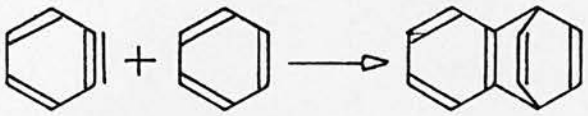
Furthermore reaction of cis and trans 1, 2-dichloroethene with benzyne both gave [2+2] adducts of mixed cis and trans stereochemistry, indicating a non-concerted thermal addition process.

Thermal [2+4] reactions of benzyne have been discussed above and one of the greatest uses of benzyne as a synthetic intermediate is its ability to undergo Diels-Alder additions to almost all diene systems. Addition to furan has already been mentioned (p.14) and provides a very simple route to 1, 4-dihydronaphthalen-1, 4-endoxide; similarly addition to tetraphenylcyclopentadienone followed by elimination of carbon monoxide gives 1, 2, 3, 4-tetraphenylnaphthalene in excellent yield.[88]

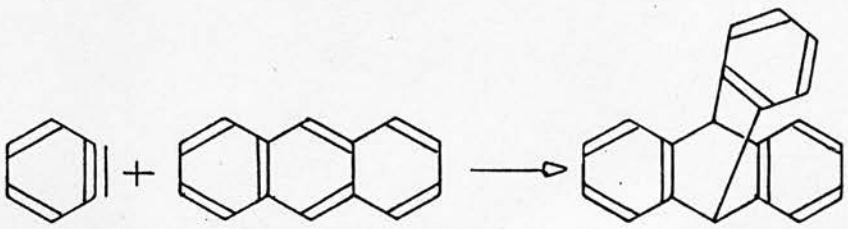


The greatest utility of this reaction is perhaps as a confirmation of the intermediacy of benzyne in a proposed reaction mechanism.

The reactivity of benzyne is so great that it will react with benzene to yield the [2+4] adduct benzobicyclo[2, 2, 2]octatriene.[89]

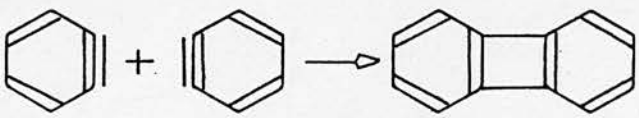


In the presence of silver ions a non-concerted [2+2] addition is also observed which earlier workers[90] had assumed to be a primary process, due to the presence of silver ions in the reaction system as an unobserved contaminant. Ready addition of benzyne to anthracene is a further commonly observed reaction of benzyne with an aromatic system.[91]



This reaction is the simplest and most convenient route to triptycene.

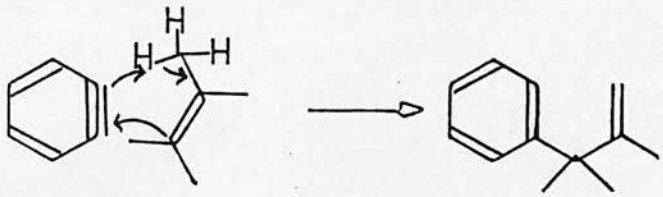
In the absence of other reactants benzyne will react with itself in a [2+2] reaction and this provides an excellent route to the strained biphenylene system.[74]



Yields however are variable and tend to depend greatly upon both the solvent used and the precursor from which the benzyne is derived.[92]

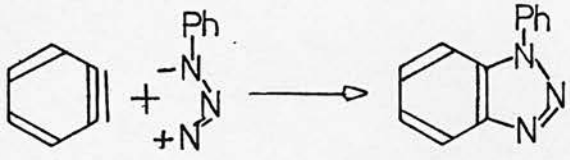
The [2+2] reaction of benzyne with cis and trans 1, 2-dichloroethene discussed earlier (p. 18) is typical of such benzyne reactions; it is however to some degree a special case since if the olefin has an allylic hydrogen then there will be a competing 'ene' reaction; this is observed

with tetramethylethene.



The benzocyclobutane derivative expected from [2+2] addition was not present.[73]

1, 3-Dipolar species react readily with benzyne and this class of reaction has proved a useful route to a large number of benzo fused heterocycles; the reaction of benzyne with phenylazide provides a good illustration.[73]



Two less commonly observed reactions of benzyne are hydrogen abstraction which may be regarded as benzyne acting as a diradical,[77] and benzyne insertion into a C-H bond;[93] neither of these reactions is of great synthetic utility.

This review, by necessity, has been extremely superficial but several comprehensive reviews on benzyne chemistry are available.[92, 94]

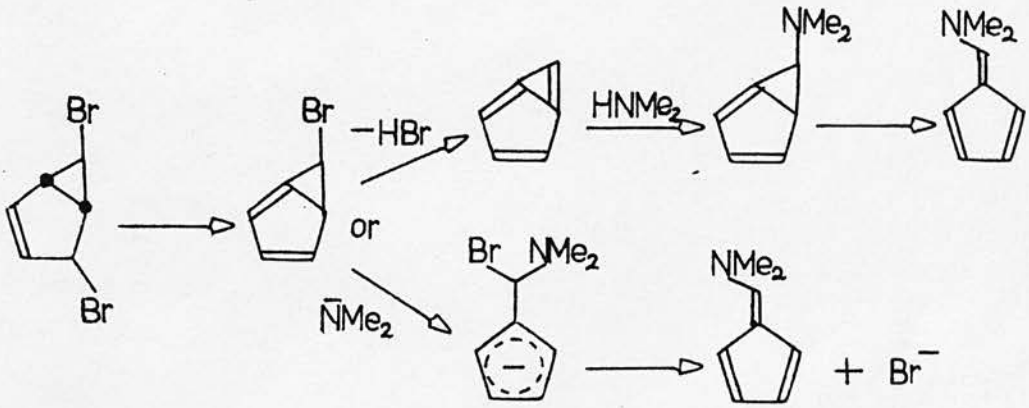
1, 3- and 1, 4-Didehydrobenzenes

Using MINDO/3 Dewar[81] calculated the geometries and heats of formation of 1, 3- and 1, 4-didehydrobenzene. He concluded that for singlet 1, 3-didehydrobenzene there was only one minimum on the energy surface and that this was represented by the bicyclo[3, 1, 0]hexatriene structure.

ΔH_f(IP) 492kJ.mol^{-1}

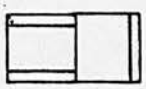
This was in agreement with the earlier predictions of Hess and Schaad.[95] Most significantly Dewar's estimate of ΔH_f for this species of 492 kJ mol^{-1} was not significantly different from that for the readily accessible 1, 2-didehydrobenzene (494 kJ mol^{-1}).

Evidence for 1, 3-didehydrobenzene as a reactive intermediate is scarce; Berry[96] claims to have observed it using time-resolved mass spectrometry and optical spectrometry from the flash photolysis of benzenediazonium-3-carboxylate. Bertorello[97] thermolysed solid 3-carboxybenzenediazonium chloride and concluded from the isolation of chlorobenzene (0.5%) that the 1, 3-dehydro intermediate had been present. However Berry's experiments lack any firm chemical evidence while Bertorello's experiments could be regarded as less than conclusive. A recent claim by Washburn[98] to have generated bicyclo[3.1.0]hexatriene from exo-exo-2, 6-dibromobicyclo[3.1.0]hex-3-ene is open to considerable doubt since his observations can be accommodated by a mechanism which invokes relatively stable intermediates and does not require the intermediacy of 1, 3-didehydrobenzene.[99]



Dewar's predictions on 1, 4-didehydrobenzene were that there were two minima on the energy surface for the intermediate; the lower energy minimum corresponded to a 1, 4-diradical, probably singlet and the high energy minimum to bicyclo[2.2.0]hexatriene.

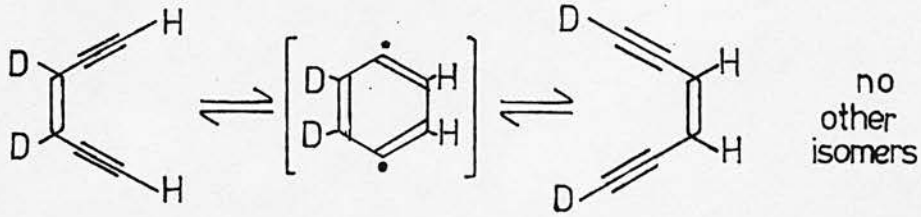
ΔH_f(IP)560kJ.mol^{-1}



ΔH_f(IP)640kJmol^{-1}

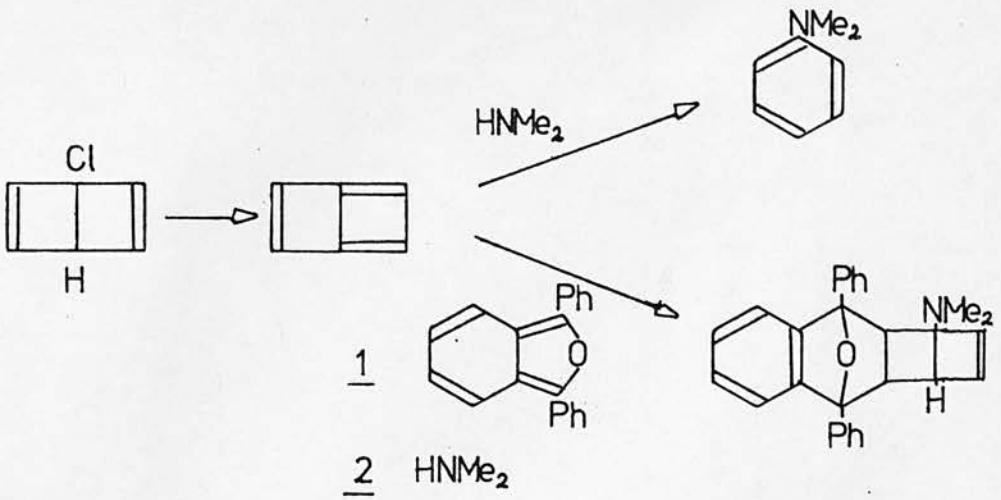
These observations were of interest since as well as Berry[100] having used mass spectroscopy and optical spectroscopy to observe a possible 1,4-didehydro intermediate from benzenediazonium-4-carboxylate, and Bertorello[101] having isolated 3-chloronitrobenzene from the thermolysis of 4-carboxy-3-nitrobenzenediazonium chloride, more convincing chemical evidence existed for both the 1,4-diradical and bicyclic structures.

Bergman[102] had thermolysed cis-1,5-hexadiyn-3-ene and had obtained from deuterium labelling evidence that the compound isomerised via a symmetrical intermediate.



Thermolysis of the diyne in a variety of solvents gave rise to some products compatible with the proposed 1,4-diradical intermediate, and taken together these two separate observations give strong support to the claim that diradical 1,4-didehydrobenzene had been generated.

Breslow[103] has shown that 3-chloro[2.2.0]bicyclohexadiene reacts in the presence of lithium dimethylamide at 0^{o} to give an intermediate which subsequently reacts to form dimethylaniline and can be trapped with 1,3-diphenylisobenzofuran; this intermediate adduct is then thought to react further with dimethylamine.



Considerable experimental evidence was presented including that from deuterium labelling experiments which taken together strongly indicated the intermediacy of bicyclo[2. 2. 0]hexatriene.

Acylarylnitrosamines

Early Chemistry and Mechanism

The first member of this family of compounds to be recognised was N-nitrosoacetanilide (NNA) which was synthesised by Fischer[104] in 1876 and isolated as a pale yellow solid. Advances in the mechanism of the decomposition of this compound resulted from von Pechmann[105] erroneously concluding that the product of acetylation of aqueous alkaline benzenediazonium compounds was NNA; the compound which he had synthesised was the isomeric benzenediazoacetate and in ignorance of this error Hantzsch[106] proposed a tautomerism between NNA and benzenediazoacetate.

$$PhN(NO)Ac \rightleftharpoons PhN{:}N{\cdot}OAc$$

As was to be shown later the fact that NNA and benzenediazoacetate reacted similarly was not due to tautomerism but to the non-reversible rearrangement of NNA to the diazo compound.

The demonstration that arene diazotates, when reacted with acetic acid or acetyl chloride in the presence of aromatic substrates, gave biaryls,[107] and that the decomposition of NNA in benzene gave biphenyl[108] was seen as further evidence for the tautomerism theory.

The Development of Chemistry and Mechanism

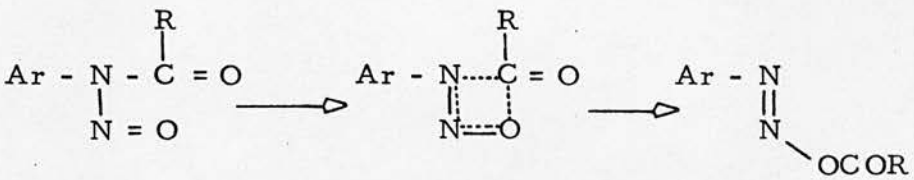
The reactions of acylarylnitrosamines in aromatic solvents to produce biaryls were used by Grieve and Hey[109] in their classical work on the establishment of free radicals as reactive intermediates and Hey proposed a basic mechanism for the decomposition.[110]

$$PhN(NO)Ac \rightleftharpoons PhN{:}N{\cdot}OAc \xrightarrow[R.D.S.]{} Ph^{\cdot} + N_2 + {}^{\cdot}OAc$$

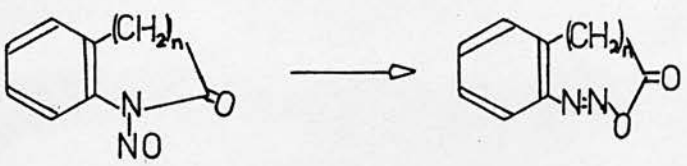
The proposal that the rate determining step (R.D.S.) was the homolysis of the diazo ester was based upon the fact that Hey had observed the rate of nitrogen evolution to be first order in most solvents.

The first challenge to this very simple mechanism came from Huisgen and Horeld[111] who showed that NNA coupled with 2-naphthol to give 1-phenylazo-2-naphthol at the same rate as nitrogen was evolved in the absence of 2-naphthol. The conclusion from this was that the diazoester reacted or decomposed rapidly upon its formation and the rate determining step was that which controlled the rate of diazoester formation.

The mechanism of diazoester formation and thus the nature of the rate determining step was independently investigated by Hey[112] and Huisgen[113] and shown to be intramolecular and non-reversible.



This mechanism which had been based on kinetic evidence was supported by Huisgen's illustration[114 115] that the rearrangement would only take place when the aryl and carboxylate groups could take up a trans configuration in the diazoacyloate. This was achieved by attaching the R group of the acylarylnitrosamine to the 2-position of the aryl moiety (1) and showing that rearrangement would only take place to the bicyclic benzenediazoacyloate (2) when the non-aromatic ring was nine membered, or greater, in order to accommodate the trans diazo system (Scheme 1)

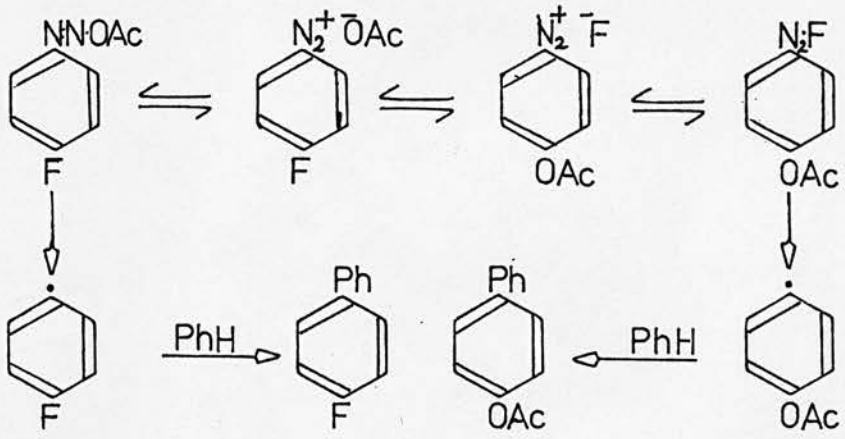


(1) (2)

Scheme 1

Although De Tar[116] had shown that in a solution of sulphuric acid in methanol NNA decomposed heterolytically to yield anisole there

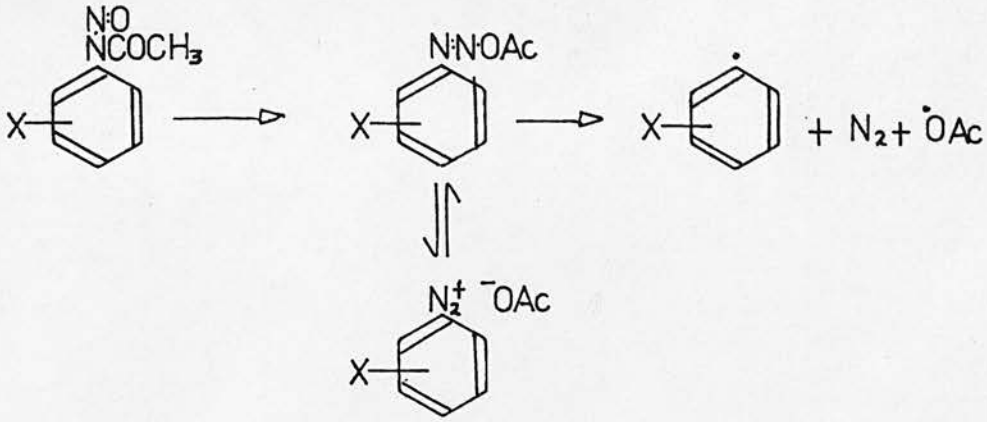
was little other evidence for heterolytic dissociation of the diazoacetate to benzenediazonium and acetate ions. It was therefore a significant mechanistic advance when Suschitzky[117, 118] demonstrated that when N-nitroso-4-fluoroacetanilide was allowed to decompose in benzene both 4-fluorobiphenyl and 4-acetoxybiphenyl were products; the presence of the latter compound could best be rationalised in terms of ion pairs (Scheme 2).



Scheme 2

N-Nitroso-2-fluoroacetanilide similarly yielded 2-acetoxybiphenyl, although the 3-isomer and all other halo-substituted acylarylnitrosamines failed to exhibit any evidence of exchange. Suschitzky then proceeded to show that this diazo-diazonium dissociation was general for acylarylnitrosamines[117] by showing the presence of 4-acetoxybiphenyl when N-nitroso-4-fluorobenzanilide was allowed to decompose in benzene along with a series of substituted acetylarylnitrosamines.

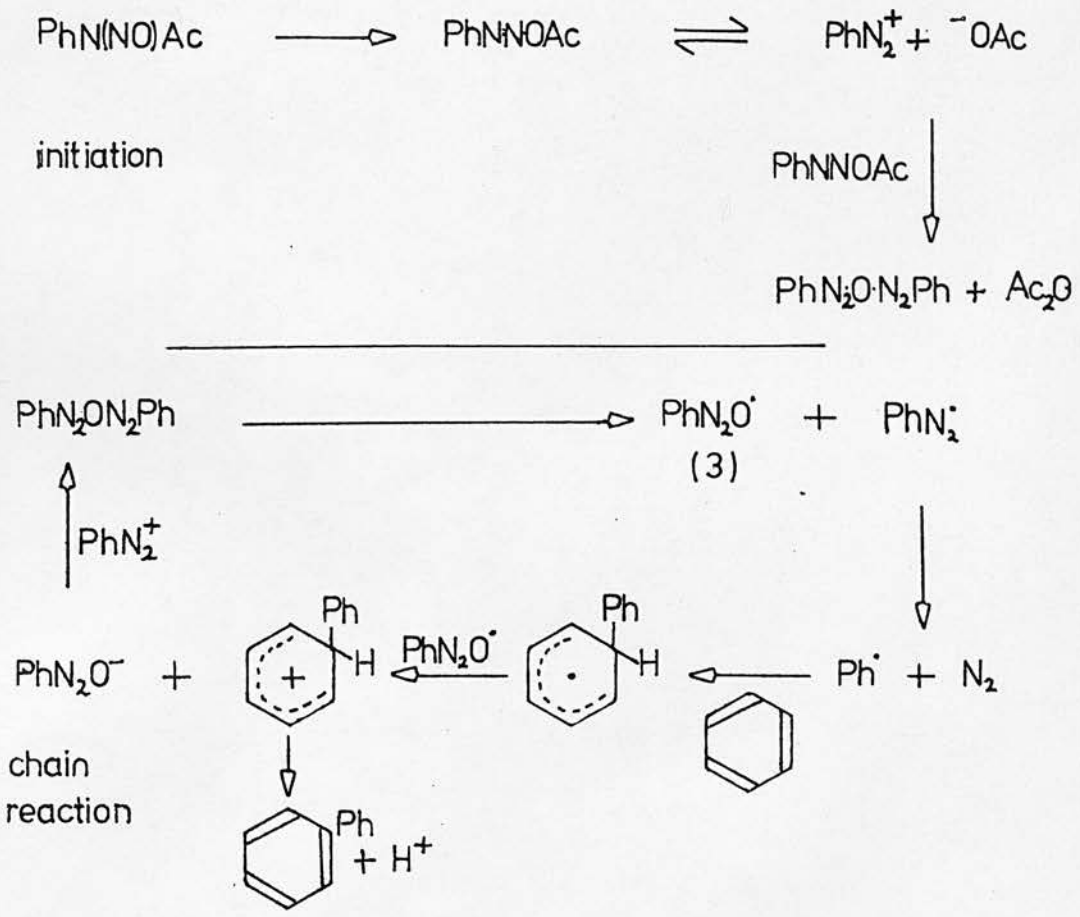
The accepted mechanism in 1962 for the decomposition of acylarylnitrosamines in benzene and most other solvents was still essentially that suggested by Huisgen and Horeld in 1949, with the inclusion of the dissociation of diazoester to diazonium acetate (Scheme 3).



Scheme 3

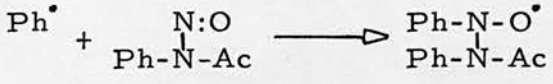
When NNA was decomposed in most organic solvents only a low yield of carbon dioxide was recorded, and the principal acetoxy derived product was always acetic acid in high yield. It was therefore surprising that despite what was known at this time about the very rapid fragmentation of acetoxy radicals to carbon dioxide and methyl radicals that the high yields of acetic acid were attributed to hydrogen abstraction by acetoxy radicals[117, 118] - a reaction unknown for acetoxy radicals in any other system. The other aspect of the decomposition of acylarylnitrosamines in benzene which was not satisfactorily resolved was the absence of dihydrobiphenyls; these were observed[119] when aryl radicals from diaroyl peroxides reacted with benzene and were considered to arise from disproportionation of arylcyclohexadienyl radicals to biaryls and dihydrobiaryls.

The unsatisfactory mechanism for the decomposition of acylarylnitrosamines in benzene (Scheme 3) was superceded in 1964 by a more elegant mechanism proposed by Rüchardt and Freudenberg[34] which encompassed and explained all of the apparent inconsistencies (Scheme 4).



Scheme 4

In support of this mechanism Rüchardt presented evidence from e. s. r. spectroscopy[34, 120] of a long-lived radical to which he assigned the diazotate structure (3). Hey and Perkins[121] challenged this assignment and Chalfont and Perkins[122] showed by independent synthesis that the radical which Rüchardt was observing by e. s. r. spectroscopy was (N-phenylacetamido)phenylnitroxide (PAPN) which formed by addition of a phenyl radical to NNA (Scheme 5)



Scheme 5

Chalfont and Perkins then proposed that the PAPN radical was the chain carrier.

This proposal was shown to be incorrect by Cadogan and Paton[123] who demonstrated by e. s. r. spectroscopy that the PAPN signal could be quenched in aromatic solvents with easily abstractable hydrogen atoms, but that in all aromatic solvents there was a weak signal which they assigned to the diazotate radical (3) proposed by Rüchardt; they showed that this was a σ radical and not a π radical as had been suggested, but concluded that this was the species necessary for Rüchardt's scheme. From his work on the decomposition of NNA in ether, which appeared to follow a mechanism analogous to that in benzene, except that the diazotate radical was absent, Cadogan[124] suggested that the oxidising species in ether was the benzenediazonium cation which was reduced to the phenylazo radical, and extended this hypothesis[125] to suggest that while Rüchardt's phenyldiazotate radical (3) may be necessary as a phenyl radical initiator a satisfactory scheme for the decomposition of NNA in benzene involving the benzenediazonium cation as oxidant could be proposed (Scheme 6).

$$Ph^{\cdot} + C_6H_6 \longrightarrow (Ph{\cdot}C_6H_6)^{\cdot}$$

$$(Ph{\cdot}C_6H_6)^{\cdot} + PhN_2^{+} \longrightarrow (Ph{\cdot}C_6H_6)^{+} + N_2 + Ph^{\cdot}$$

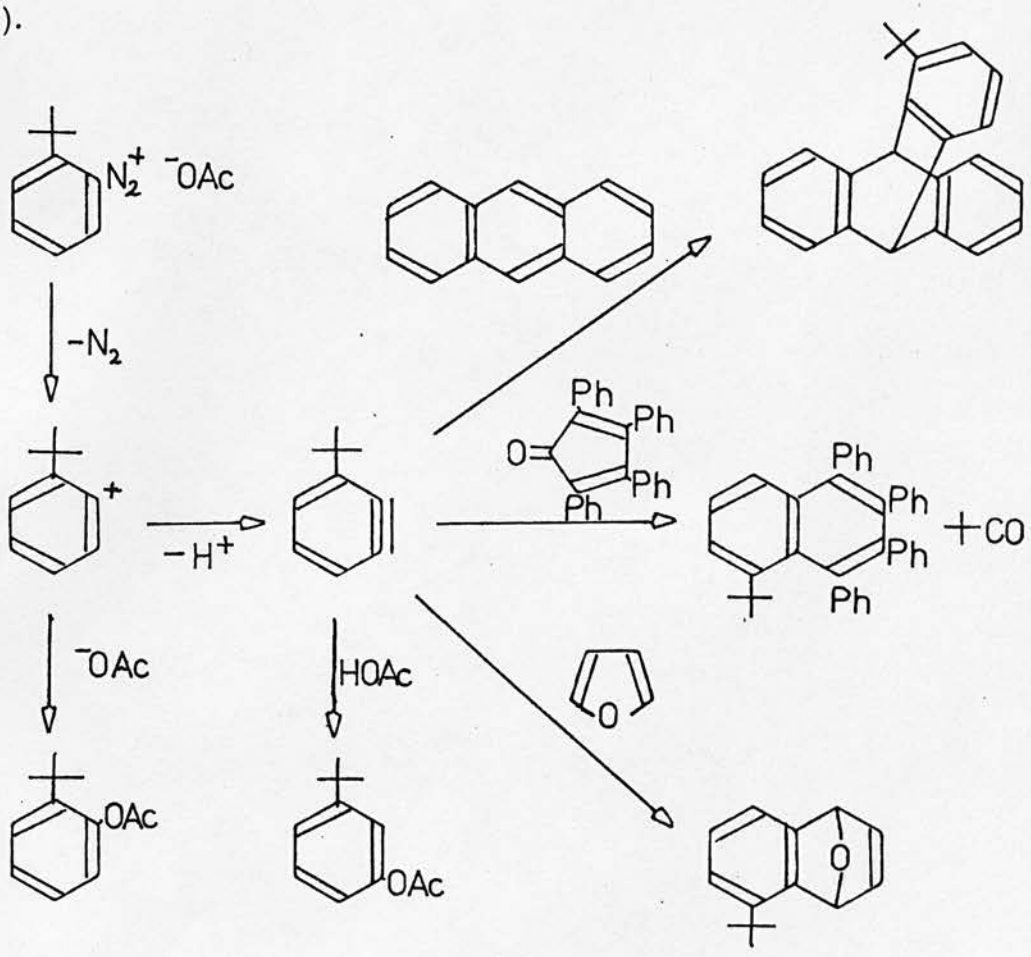
$$(Ph{\cdot}C_6H_6)^{+} + AcO^{-} \longrightarrow Ph{\cdot}Ph + AcOH$$

Scheme 6

Arynes from Acylarylnitrosamines

In 1952 Cadogan, Hey and Williams[126] observed that when N-nitroso-2-t-butylacetanilide was decomposed in benzene the major product was 3-t-butylphenylacetate, there was a lesser amount of the 2-isomer and only 4% of the anticipated 2-t-butylbiphenyl. The significance of this observation was not realised until 1964 when Cadogan and Hibbert[127] showed that N-nitroso-2-t-butylacetanilide in benzene in the presence of a variety of aryne traps gave aryne derived adducts with concomitant reduction in the yields of 3-t-butylphenylacetate.

It was proposed[128] that steric destabilisation of the 2-t-butylbenzenediazonium cation by the bulky t-butyl group led to rapid loss of nitrogen and formation of the 2-t-butylphenyl cations which could either react with acetate ion to give 2-t-butylphenylacetate or lose the aromatic proton adjacent to the cation centre to give 3-t-butylbenzyne; this could add to aryne traps or in the absence of these add to acetic acid with the acetate ion entering the less hindered 3-position (Scheme 7).



Scheme 7

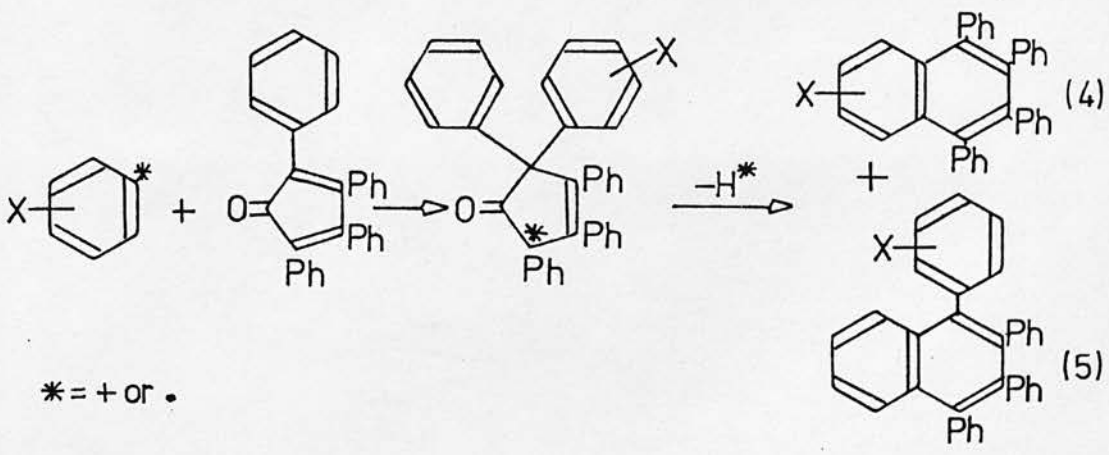
Support for the directing effect of the t-butyl group comes from the demonstration that authentic 3-t-butylbenzyne in ammonia reacts to give 99% of the sterically favoured 3-t-butylaniline.[128] The addition of acetic acid to 3-t-butylbenzyne was attributed to the shielding effect of the t-butyl group preventing other reaction since addition of acetic acid is not a common reaction; in keeping with this a 79%

yield of 2, 5-di-t-butylphenylacetate was observed from the decomposition of N-nitroso-2, 5-di-t-butylacetanilide in benzene.

Although steric acceleration by a bulky group can explain the genesis of the aryne in the 2-t-butyl case the subsequent observation that NNA and 3- and 4-substituted acylarylnitrosamines when decomposed in solution in the presence of tetraphenylcyclopentadienone (tetracyclone), anthracene and 1,3-diphenylisobenzofuran gave aryne adducts merited further investigation.[129]

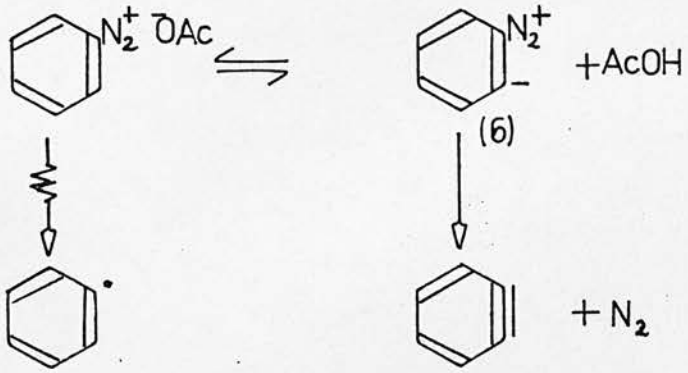
Cadogan and Brydon had noted that while the decomposition of NNA in benzene gave over 50% yields of biphenyl, when tetracyclone was present the biphenyl yield was only 16% and the yield of the benzyne adduct, 1, 2, 3, 4-tetraphenylnaphthalene, was 25%. When NNA was decomposed in the presence of tetracyclone in benzene-furan mixtures the yields of 1, 2, 3, 4-tetraphenylnaphthalene fell from 25% in neat benzene to 1% in neat furan, despite this none of the benzyne adduct with furan was observed, the main product in neat furan being the free radical derived 2-phenylfuran in 23% yield.

Since the evidence for the presence of benzyne was apparently contradictory it was necessary to carefully examine the nature of the benzyne-type addition reactions observed; the intermediacy of aryl free radicals or aryl carbonium ions could be eliminated since addition of either species to tetracyclone would result in an intermediate which could cyclise onto either the aryl or phenyl group (Scheme 8).



Scheme 8

Since only products of type (4) were observed Cadogan suggested that an arynoid intermediate could be involved[129] which could decompose to benzyne or return to a benzenediazonium ion and thus to free radicals; the betaine (6) was favoured as the arynoid intermediate since the reversible elimination-addition of nitrogen was considered unlikely (Scheme 9).



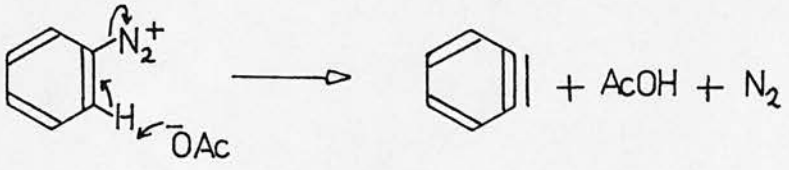
Scheme 9

The acetate ion was assumed to be acting as base and the arynoid species (6) in equilibrium with the diazonium cation explained the variable radical-aryne product ratios. What was considered to be additional evidence for this arynoid was the observation by Cook[130] that the reaction of NNA with dimethyl acetylenedicarboxylate gave tetramethyl naphthalen-1, 2, 3, 4-tetracarboxylate which he proposed was an arynoid derived product since authentic benzyne was known to give tetramethyl dibenzo[a, e]cyclooctatetraene-5, 6, 11, 12-tetracarboxylate; this anomolous reaction was however subsequently shown by Baigrie[131] to be free radical in nature (see 'The Addition of Aryl Radicals to Alkynes and Related Reactions,' p. 39).

The mechanism involving reversible unimolecular dissociation of the betaine (6) to benzyne (E_1 cb mechanism) was in conflict with the observation of Cadogan and Cook[129] that in competition experiments involving the decomposition of NNA in the presence of pairs of arynophiles adduct ratios identical to those observed with authentic benzyne were obtained.

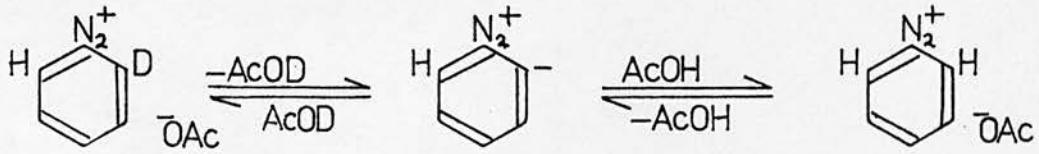
The observation by Rüchardt[132] that arene diazonium salts in the presence of potassium acetate in benzene gave good yields of arynes

was support for the role of acetate as the proton abstracting species in this system; he suggested however that the reaction proceeded via a bimolecular mechanism (E_2) with concerted abstraction of a proton and loss of nitrogen (Scheme 10) although he did not present any experimental support for this proposal.



Scheme 10

Buxton and Heaney[133] gave support to the E_1cb mechanism proposed by Cadogan by reporting that [2-^{2}H] benzenediazonium chloride when decomposed in the presence of potassium acetate and anthracene in 1, 2-dichloroethane yielded benzyne derived products containing less than 50% deuterium label. Ignoring isotope effects 50% deuterium labelling would have been expected for an E_2 mechanism and taking isotope effects into account,[134] labelling greater than 50% would be expected; it therefore appeared that the diazonium ion was undergoing reversible formation to the betaine (6) (Scheme 11).



(6)

Scheme 11

Simultaneously however Cadogan, Murray and Sharp[135] were examining similar systems and they showed that in experiments with [2-^{2}H] benzenediazonium salts and potassium acetate in benzene slightly over 50% of the deuterium label was retained in the benzyne derived adducts. Using the reaction of acetanilide with 4-chlorobenzoyl nitrite[136] which had previously been developed by Cadogan and co-workers as a high yield route to arynes via in situ generated

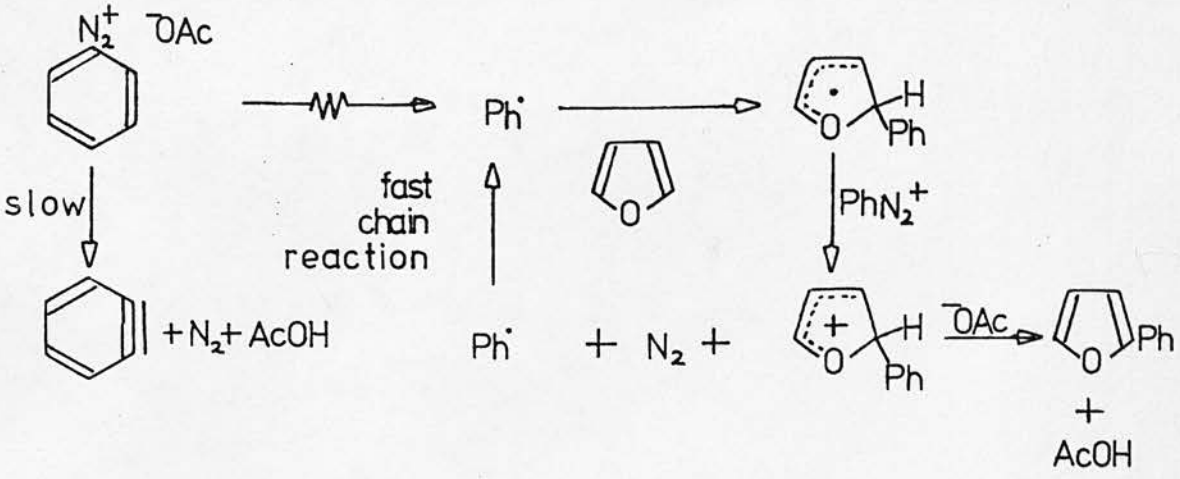
acylarylnitrosamines, they showed that benzyne adducts derived from [2, 4, 6-$^{2}H_3$] acetanilide in the presence of tetracyclone and acetic acid had only lost 1 mole of deuterium per mole of acetanilide; similar results were obtained using [2, 4, 6-$^{2}H_3$] benzenediazonium tetrafluoroborate in the presence of acetate ions and benzyne trap; finally unlabelled benzenediazonium tetrafluoroborate was reacted as previously in the presence of acetate ion and acetic [^{2}H] acid and no deuteration was observed in either the benzyne or free radical derived products. Buxton and Heaney[137] repeated their experiments and found their results to be in accord with those of Cadogan, Murray and Sharp.

Further labelling studies by Cadogan, Murray and Sharp[138] using ^{15}N labelled NNA established that neither the benzyne nor free radical decomposition pathways involved a reversible nitrogen loss.

The mechanistic conclusions which were drawn from these results were that the formation of benzyne from NNA by acetate attack on the benzenediazonium cation proceeded either via a non-reversible E_1cb mechanism in which loss of nitrogen from the betaine (6) was much faster than re-protonation or via a concerted E_2 mechanism;[135] in either case nitrogen loss was non-reversible.[138]

The only remaining major inconsistency in the comprehensive mechanistic scheme developed for NNA decomposition in aromatic solvents was the failure of benzyne derived from NNA to add to furan in the same [2+4] manner as that derived from other sources, and the effect of furan in lowering the yields of benzyne adducts with other dienes.[129]

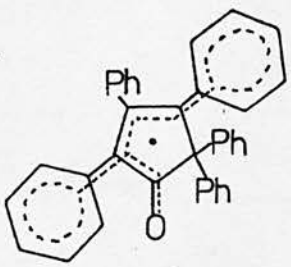
Mitchell[139] had established that the rate of attack of benzenediazonium derived phenyl radicals on mixtures of furan and benzene gave a higher K furan/benzene value than that observed when the phenyl radicals were derived from other sources; one of his rationalisations for this was that when NNA decomposed in furan a very fast radical chain process, analogous to that for NNA in benzene, was diverting the benzenediazonium cations into the radical chain process, before the relatively slow ionic benzyne formation could take place (Scheme 12).



Scheme 12

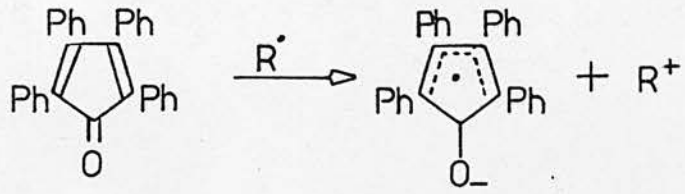
Although 2-phenyl furan is the major product both Mitchell[139] and Rüchardt[140] had observed the benzyne-furan adduct, 1,4-dihydro-naphthalen-1,4-endoxide as a minor product.

Murray[141,142] re-examined the anomolous behaviour of NNA with furan compared with that with tetracyclone and suggested that tetracyclone could be acting to inhibit the radical chain process either by trapping the phenyl radical chain carriers to give an adduct (7) which would be a persistent radical due to delocalisation and resistance to oxidation and hence be a poor chain carrier and block the radical chain process.



(7)

Alternatively the tetracyclone might be promoting benzyne formation by the oxidation of chain carrying radicals to give a tetracyclone radical anion (8) and a cation (Scheme 13).

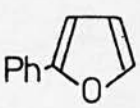
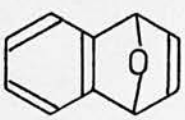


Scheme 13

Murray reasoned that in either case the presence of olefins which showed some structural resemblance to tetracyclone but were not dienes might inhibit the free radical chain process and allow time for benzyne to be formed and to react with dienes present, and in particular furan.

In order to test this hypothesis he decomposed NNA in benzene-furan solution at 60° and compared the results with those obtained when a series of olefins were added to such a solution prior to the addition of NNA; these olefins were present in the same molar quantity as NNA. The results are shown in Table 1.

Table 1

Addendum	PhOAc	Product (%) 		Ph. Ph
2, 3-diphenyl-indenone	21	8	37	2
BzCH:CPhBz	18	13	43	4
AcPhC:CHPh	11	30	23	6
$Ph_2C:CH_2$	25	6	46	2
PhCO COPh	7	42	11	10
$Ph_2C:CHPh$	15	25	27	6
trans PhCH:CHPh	17	18	32	5
$PhCH:CH_2$	22	9	42	2
none	4	50	7	10

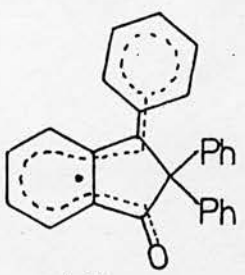
The best promotion of the benzyne derived [2+4] adduct with furan was found with 1, 1-diphenylethene although styrene, triphenylethene, 2, 3-diphenylindenone and 1, 3, 4-triphenylbut-2-ene-1, 4-dione also gave good yields.

Evidence that the alkenes were trapping phenyl radicals was obtained in the case of 1, 1-diphenylethene by the isolation of triphenylethene in 8% yield and triphenylethane in 1% yield from the reaction mixture; the high reactivity of this alkene in suppressing radical reactions was shown by the fact that when present as only 0. 1 mol per mole NNA the yield of benzyne derived endoxide product was 29%.

The use of similar addenda in the reaction of NNA with anthracene[142] in benzene showed the yields of triptycene to be the same as (17%) or less than those obtained in the absence of olefin with the lowest yield (5%) being observed in the case of 1, 1-diphenylethene. Murray rationalised these observations in terms of the high reactivity of anthracene towards free radicals.

E. s. r. spectroscopy[143] failed to observe any hydrocarbon radicals in the case of NNA decomposed in benzene and 1, 1-diphenylethene, indicating that any intermediate adduct radical is relatively short lived. In the case of tetracyclone however Cadogan, Murray, Paton[143] and coworkers observed a poorly defined signal which they assigned to the phenylated tetracyclone system (7).

With 2, 3-diphenylindenone the e. s. r. spectrum was well-defined and analysis was in accord with the radical resulting from phenylation at the 2-position of 2, 3-diphenylindenone (9).



(9)

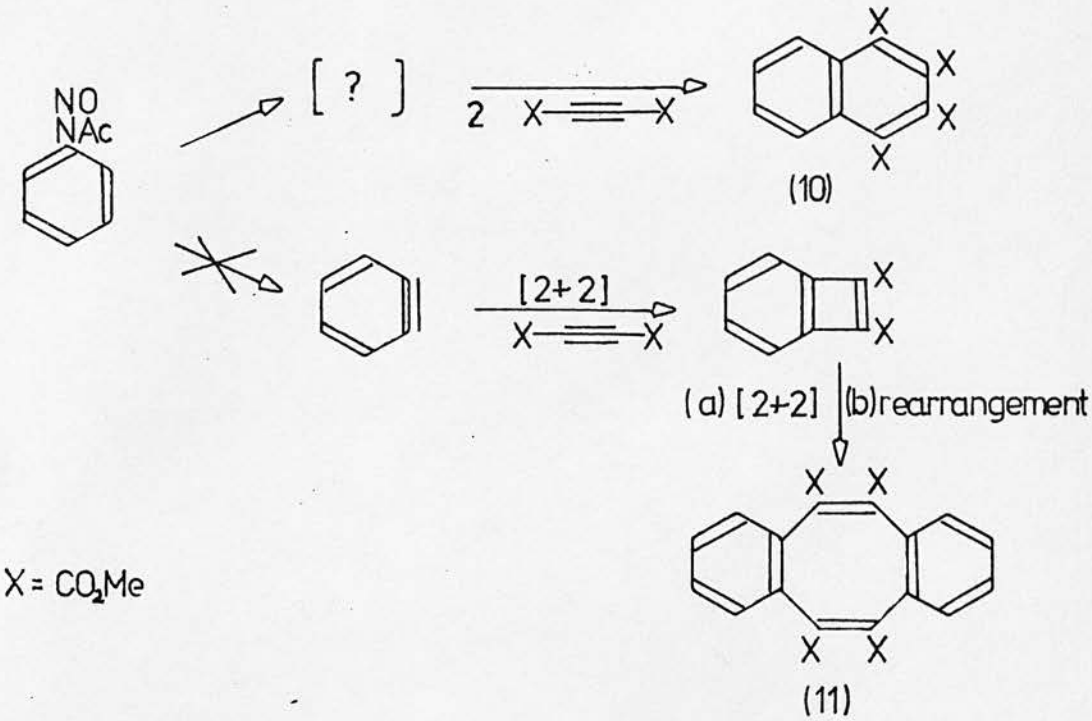
Support for this assignment[143] was obtained by synthesising 2-phenyl-3-(4-t-butylphenyl)indenone and observing a simplification in the e. s. r. spectrum due to the removal of splitting with the proton on the

4-position of the phenyl group; as was predicted 2-(4-t-butylphenyl)-3-phenyl indenone gave a spectrum identical to that for the 2, 3-diphenyl indenone derived species (9).

These synthetic and e. s. r. approaches provided a satisfactory explanation for the anomolous behaviour of NNA derived benzyne in furan and tetracyclone in terms of the already known reactions and reactivity of NNA and removed some of the last mechanistic obscurities in the behaviour of NNA with dienes.

The Addition of Aryl Radicals to Alkynes and Related Reactions

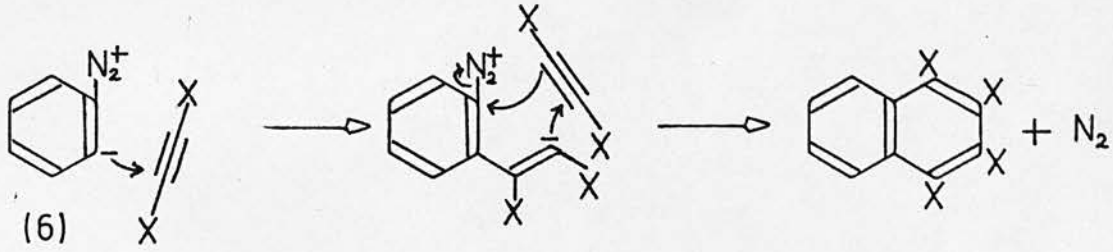
The reaction of N-nitrosoacetanilide (NNA) with dimethyl acetylenedicarboxylate (DMAD) in benzene to form tetramethyl naphthalen-1, 2, 3, 4-tetracarboxylate (10) was observed by Cook[130] when attempting to obtain tetramethyl dibenzo[a, e]cyclooctatetraene-5, 6, 11, 12-tetracarboxylate (11) by [2+2] addition of benzyne derived from NNA to the acetylene (Scheme 14).



Scheme 14

Other products obtained from the reaction were dimethyl 1, 2-diphenylmaleate, dimethyl 1, 2-diphenylfumarate and biphenyl.

Cook then showed that benzyne derived from benzenediazonium-2-carboxylate yielded solely the dibenzocyclooctatetraene (11) and rationalised the formation of the naphthalene tetraester (10) in terms of the betaine (6) (Scheme 15).



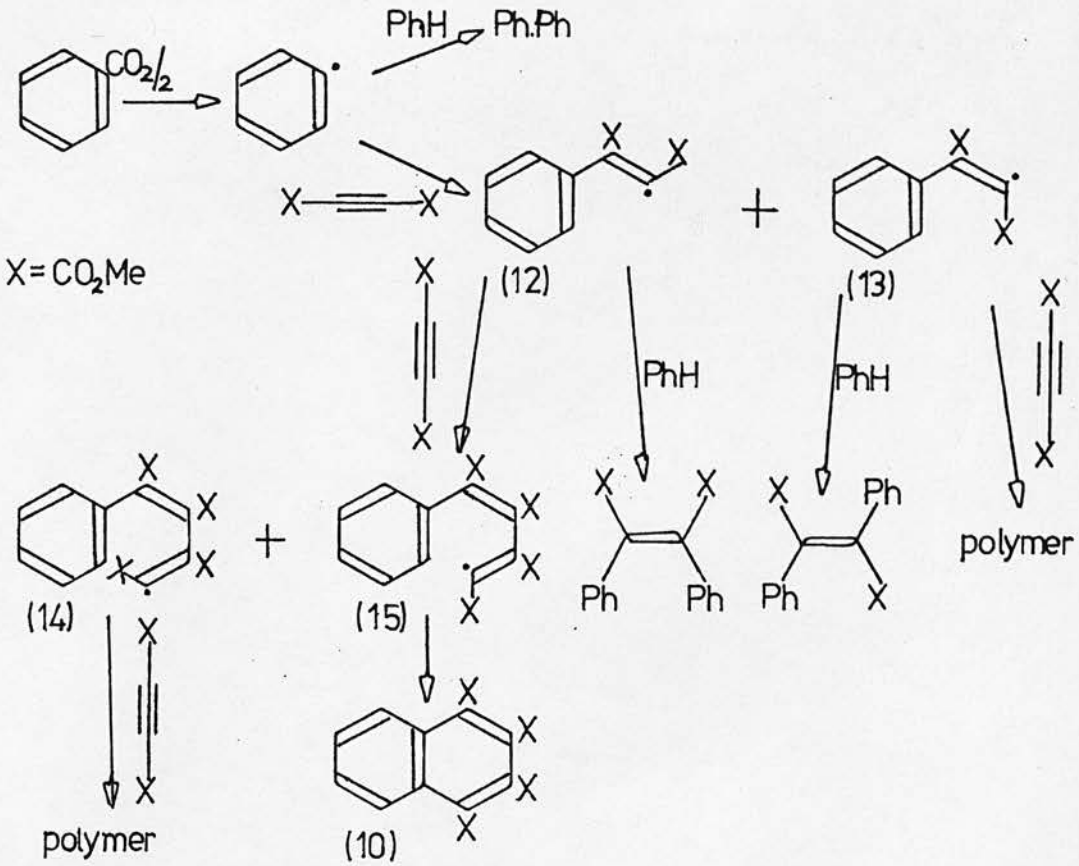
X= CO_2Me

Scheme 15

This scheme was not totally satisfactory since this betaine might well have been expected to cyclise after the addition of one molecule of DMAD to form a cinnoline derivative; the formation of fumarate and maleate derivatives was rationalised in terms of a phenyl carbonium ion mechanism while the biphenyl was considered to be most probably derived from the reaction of phenyl radicals with benzene. This proposed mechanism had the weakness of proposing novel reactive intermediates while being lacking in strong experimental evidence.

Baigrie[144] re-examined this reaction and was able to demonstrate convincingly that all three products observed by Cook could be accounted for solely on the basis of a free radical mechanism. By decomposing dibenzoyl peroxide, an authentic source of phenyl radicals, in DMAD and benzene he obtained a mixture of all three products observed by Cook from the NNA decomposition under the same conditions. Baigrie then proposed a mechanism to account for all of the products (Scheme 16).

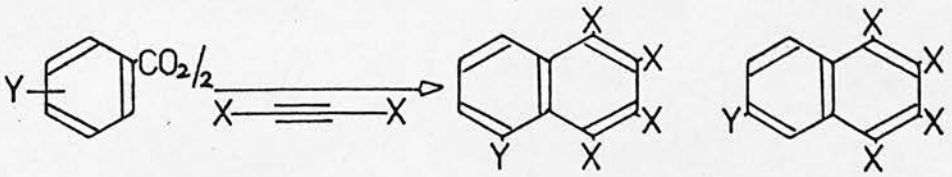
The common pathway of both the NNA and dibenzoyl peroxide reactions was further demonstrated by replacing benzene with t-butylbenzene and showing that the isomer ratios of the three dimethyl 1-phenyl-2-(t-butylphenyl)maleates and of the three corresponding fumarates from both sources were identical and independent of the aryl precursor. This indicated that attack of the styryl intermediates on the 2, 3-, and 4-positions of t-butylbenzene was of the same type in both cases and therefore free radical.



Scheme 16

Baigrie then extended the reaction by decomposing a variety of diaroyl peroxides in a 10 molar excess of DMAD at 80° and thus developed a useful route to substituted tetramethylnaphthalene-1, 2, 3, 4-tetracarboxylates;[131, 144] some representative results are tabulated in Table 2.

Table 2



Y =			
	H	50	-
	2-NO_2	0	-
	3-Cl	10.2	3.8
	3-Me	12.7	6.3
	4-Cl	-	22
	4-Me	-	18

Yields are expressed as m/100 m diaroyl peroxide.

In the case of the unsubstituted peroxide 25% of the potential phenyl radicals are accounted for by products while in the 3- and 4-substituted peroxides around 10% of the potential aryl radicals can be accounted for; this order of accountancy was general for all 3- and 4-substituents (3-Cl, 3-Br, 3-Me, 4-Cl, 4-Br, 4-Me, 4-CN). In the 2-nitro case no naphthalene products were observed.

In the dibenzoyl peroxide case Baigrie proposed[144] that the naphthalene tetraester yield of 50 m/100 m peroxide could be explained in terms of quantitative decarboxylation of the peroxide to phenyl radicals, which upon addition to DMAD gave cis- and trans-styryl radicals in a 1:1 ratio; the trans-styryl radical (13) being in the wrong configuration for cyclisation formed a polymer with additional DMAD while the cis-styryl radical (12) added to a further molecule of DMAD to give phenylbutadienyl radicals (14 and 15) in a 1:1 ratio; only the cis-radical (15) was in the correct configuration for cyclisation and consequently only 25% of the initially formed phenyl radicals were incorporated in the naphthalene tetraester product (10). He was unable to offer any explanation for the large reduction in yields of substituted naphthalene tetraesters from the 3- and 4-substituted diaroyl peroxides,

although he noted that this diminution was independent of the electron withdrawing or donating properties of the substituent; similarly he was unable to offer any reason for the total absence of desired product in the bis-2-nitrobenzoyl peroxide case. It was of significance however that when the mixed benzoyl-4-nitrobenzoyl peroxide was decomposed in DMAD the total accountancy of naphthalene tetraester products was only 20 m/100 m peroxide with the naphthalene product derived from the phenyl radical predominating in a ratio of 2:1 over the substituted product.

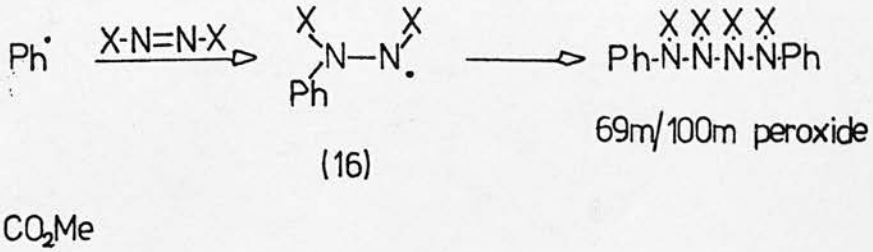
Bis-2-naphthoyl peroxide reacted analogously with DMAD to give a mixture of phenanthrene and anthracene tetraesters in low yield (6 m/100 m peroxide).

Bis-2-phenylbenzoyl peroxide failed to decarboxylate efficiently and while giving the cyclisation product of the 2-phenylbenzoyloxy radical, 3,4-benzocoumarin as 37 m/100 m peroxide, failed to give any of the anticipated dimethyl phenanthren-9, 10-dicarboxylate; similarly, through failure to decarboxylate, bis-2-theonyl peroxide gave none of the desired tetramethyl benzothiophen-4, 5, 6, 7-tetracarboxylate.

Changing the substituents on the alkyne used would obviously allow access to a more varied selection of naphthalene derivatives, but results obtained in this area were disappointing. While ethyl propiolate and dibenzoyl peroxide gave a mixture of at least two disubstituted naphthalenes (total: 27 m/100 m peroxide) these could not be separated; n.m.r. indicated that one of the products was diethylnaphthalen-1, 3-dicarboxylate but the substitution pattern of the second isomer could not be deduced.

Phenylacetylene and a variety of mono- and di-alkylacetylenes reacted with dibenzoyl peroxide to give benzoic acid and large amounts of polymeric tar, but failed to yield any bicyclic products.

The reaction of dibenzoyl peroxide with dimethyl azodicarboxylate at 80°, [145] while failing to yield any bicyclic benzotetrazine derivatives gave the novel tetramethyl 1,4-diphenyltetrazan-1, 2, 3, 4-tetracarboxylate system in good yield (Scheme 17).



Scheme 17

The product was thought to result from dimerisation of the nitrogen centred radical (16).

Programme of Research

The use of alkenes to promote the ionic formation of benzyne and benzyne derived products from the decomposition of N-nitroso-acetanilide (NNA) in benzene-furan mixtures has been developed by Murray. It was intended to continue this work by looking for alkenes whose presence resulted in higher yields of NNA derived benzyne in a standard benzene-furan system using Murray's observations as a basis for determining which substituents on the alkene appeared to enhance benzyne formation, and thus allow a more critical assessment of the mechanistic role of benzyne promoters. It was also hoped to show the generality of the promoter effect by decomposing a series of acetylaryl-nitrosamines in benzene-furan-promoter solutions as a potential synthetic route to 5- and 6-substituted 1,4-dihydronaphthalen-1,4-endoxides; more broadly it was hoped that ionic reactions of acetylarylnitrosamines could be promoted and observed in preference to the normally observed free radical reactions.

The reaction of diaroyl peroxides with a series of acetylenes to yield substituted naphthalene products has been developed by Baigrie; in many cases the yields of products were low or undetectable and it was hoped to determine why the reactions gave low yields and to obtain a better understanding of the major reaction mechanisms effective in the system. It was then hoped to develop the cyclisation reaction, principally by the generation of styryl radicals and allowing these to react with dimethylacetylenedicarboxylate, hopefully to yield naphthalen-1,2-diesters.

EXPERIMENTAL CONTENTS

Page

Symbols and Abbreviations

b.p.	boiling point
m.p.	melting point
t.l.c.	thin-layer chromatography
Rf	ratio of distance moved by substance to distance moved by solvent front
g.c.	gas-liquid chromatography
i.r.	infra red
w	weak
m	medium
s	strong
n.m.r.	nuclear magnetic resonance
s	singlet
d	doublet
t	triplet
q	quartet
m	multiplet
u.v.	ultraviolet
e.s.r.	electron spin resonance
M^+	mass of molecular ion
m/e	mass to charge ratio
m.s.	mass spectrometry
w/v	weight per volume
w/w	weight per weight
m/100m	moles per 100 moles
h.s.l.c.	high speed liquid chromatography

Gas Liquid Chromatography

For quantitative and analytical g.c. investigations a Pye 104 chromatograph with flame ionisation detector was used; all columns were 2m x 2.2mm i.d. Quantitative measurements were made after calibration of the instrument with known mixtures of authentic samples and internal standards. All authentic samples and internal standards were purified before use. The carrier gas was nitrogen and the flow rates were as recommended by the manufacturer.

The following stationary phases supported on 100-120 mesh celite were used: polyethyleneglycol 20M (CAR), silicone grease (SE 30) and Apiezon L grease (APL). 'Chromosorb G' was used to support neopentylglycol succinate (NPGS).

Column Chromatography

Alumina used for column chromatography was Laporte Industries Ltd., activated aluminium oxide, type H (Brockmann activity = 1). Dry column chromatography was carried out using the method of Loev and Goodman[146] with chromatographic alumina deactivated to Brockman activity 3 and treated with Woelm fluorescent indicator for short wave u.v. (254 n.m.). Columns of the required dimensions were made up in 'C' gauge nylon tubing supplied by Walter Coles and Co. Ltd., London. After development of the column the required segments were sliced out and the products washed from the alumina with a suitable solvent. Silica gel used was chromatography grade (80-200 mesh) supplied by Fisons Scientific Apparatus. All column dimensions are given as diameter x length of packing material in the column.

High Speed Liquid Chromatography

The injection head used was of a design developed by Knox and co-workers at the University of Edinburgh;[147] the pump was a Jobling eluant delivery unit with pressure damper, normally delivering 300 p.s.i. The detector was a Cecil C.E. 212 u.v. spectrophotometer fixed at

254 n.m. with an 8µl flow cell. Columns were 5 mm i.d. x 250 mm, of polished stainless steel and slurry packed.

Hexane was passed through an alumina column to remove u.v. active contaminants and water was added to the ethyl acetate (A.R. grade) to give 0.6% water in solution. Fuller details of the practice of this technique are given elsewhere.[148]

Thin Layer Chromatography

Thin layer chromatograms were obtained on 0.3 mm layers of alumina (Merck, aluminium oxide G) or silica gel (Merck, silica gel G). Components in the developed chromatograms were detected by their fluorescence in u.v. light or by their reaction with iodine.

Nuclear Magnetic Resonance Spectroscopy

Spectra were normally obtained on a Varian E.M. 360 spectrometer operating at a frequency of 60 MHz and at a probe temperature of 33°. Where higher resolution was considered desirable a Varian HA 100 instrument operating at 100 MHz and at a probe temperature of 28° was used. Chemical Shifts were recorded in delta (δ) values in parts per million using tetramethylsilane as an internal reference ($\delta = 0.0$). Spectra were normally recorded in 10-15% w/v solution in chloroform.

Infrared Spectroscopy

Spectra were recorded on a Perkin-Elmer 157G infrared spectrameter; liquid samples were examined as thin films and solid samples as nujol mulls, supported on KCl discs.

Mass Spectroscopy

Mass spectra of compounds were recorded using an A.E.I. MS-902 double focussing mass spectrometer. Reaction mixtures were examined with a V.G. Micromass 12 single focussing gas chromatograph-mass spectrometer and this technique was frequently used to confirm the

presence of compounds in mixtures, in such cases the spectrum was generally compared with that of an authentic sample. In cases where assignment was made totally on the basis of the observed m. s. comparison was made with a positional isomer or parent compound. How such assignments were made is given in the relevant experimental sections; the m/e values and intensities of the principal peaks of these compounds are given with those of the substance with which the comparison was made in an appendix (p. 95-97).

Elemental Analysis

Microanalyses were carried out on a Perkin-Elmer Elemental Analyser 240 by Mr. J. Grunbaum, University of Edinburgh.

Melting Points

Melting points of all new compounds were determined using a Kofler hot-stage apparatus.

Solvents and Reagents

Benzene was purified by distillation of the sodium dried solvent from calcium hydride in an atmosphere of dry nitrogen. Furan, cumene and xylene were passed down a short alumina column, distilled from lithium aluminium hydride and stored over molecular sieve at 0^{o} in the dark. Petrol, unless otherwise stated, refers to light petroleum ether (b. p. 40-60^{o}); this was redistilled and stored over sodium. Ether was distilled and sodium dried where necessary.

Spinning Band Distillation

This was performed on a Nester Faust annular spinning band distillation column with a 600 mm 'Telfon' band; distillation was at a rate of 1-2 ml per hour.

Preparation of Acylarylnitrosamines

These were prepared essentially using the method described by Cadogan, Hey and Williams[126] and exemplified by the synthesis of N-nitrosoacetanilide:-

Acetanilide (3.4 g, 25 mmol), acetic acid (25 g), acetic anhydride (12.5 g), fused potassium acetate (3.4 g) and phosphoric oxide (0.1 g approximately) were stirred under anhydrous conditions at 0°. Nitrosyl chloride (2.7 g, 50 mmol, 30% w/v in acetic anhydride) was added over 0.5 h and the solution was stirred for a further 0.5 h.

The reaction mixture was then poured into a stirred ice-water slurry (400 g) and stirring continued until N-nitrosoacetanilide separated out as a pale yellow solid. This was collected and washed with cold aqueous potassium hydrogen carbonate solution (10% w/v) and then with cold water. The solid was pressed between filter papers until no moisture was apparent and finally dried over phosphoric oxide at room temperature and 0.05 mmHg pressure for 2 h.

The N-nitrosoacetanilide (3.1 g, 76%), m.p. 51° decomp. (lit 50°)[149] showed no N-H stretch in its i.r. spectrum (3400-3000 cm^{-1}) and was stored at -30°.

Other acylarylnitrosamines prepared by this method were:-

N-nitroso-2-chloroacetanilide	m.p. 46-47°	(lit 46-47°)[150]
N-nitroso-4-chloroacetanilide	m.p. 74-75°	(lit 77°)[117]
N-nitroso-2-acetoxyacetanilide	m.p. 54°	(lit)†
N-nitroso-4-acetoxyacetanilide	m.p. 76°	(lit 74°)[150]
N-nitroso-4-t-butylacetanilide	m.p. 57°	(lit 57.5°)[126]
N-nitroso-4-methoxyacetanilide	m.p. 72°	(lit 73-74°)[139]
N-nitroso-4-methylacetanilide	m.p. 72°	(lit 73°)[117]

All of these compounds decomposed upon melting.

† This is a new compound; analysis (Found: C, 53.8; H, 4.6; N, 12.2. $C_{10}H_{10}N_2O_4$ requires C, 54.1; H, 4.5; N, 12.6%).

N-Nitroso-2-thioacetoxyacetanilide and N-nitroso-3-chloroacetanilide, which are oils, were synthesised in the same manner as described above and extracted from the aqueous medium after hydrolysis of the reaction mixtures; fuller details of the isolation procedures are given in the experimental descriptions of the reactions of these compounds.

Preparation of Biaryls

a) The method described by Cadogan[30] was used and is exemplified by the synthesis of 4-methoxybiphenyl:-

A solution of 4-methoxyaniline (6.2 g, 0.05 mol) in benzene (50 ml) was added over 0.5 h to a stirred boiling solution of commercial amyl nitrite (11.7 g, 0.1 mol) and benzene (125 ml), and heating was continued for a further 3 h. The remaining benzene and amyl alcohols were removed on the rotary evaporator, and the residual black tarry products (14 g) were deposited on alumina (70 g) and chromatographed on 700 g of alumina on a 45 mm diameter wet column eluting with petrol.

The first fraction obtained (3.6 g) was crystallised from ethanol to yield 4 methoxybiphenyl (3.1 g, 34%) m.p. 90°, lit[151] 90°.

Other biaryls synthesised by this method were:-

2-chlorobiphenyl	m.p. 32-33°	(lit 32°)[151]
3-chlorobiphenyl	b.p. 115-117°/0.5mmHg	(lit 150-160°/6mmHg)[151]
4-chlorobiphenyl	m.p. 76.5-77.5°	(lit 77°)[151]
4-bromobiphenyl	m.p. 90-91°	(lit 89°)[151]
4-methoxybiphenyl	m.p. 89-90°	(lit 90°)[151]
4-methylbiphenyl	m.p. 47-48°	(lit 47-48°)[153]

b) Commercially available samples of 2- and 4-hydroxybiphenyl were acetylated with acetyl chloride in the presence of magnesium as described by Spassow[152] to give:-

2-acetoxybiphenyl	m.p. 61-63°	(lit 62-63°)[151]
4-acetoxybiphenyl	m.p. 88-89°	(lit 88-89°)[151]

4-t-Butylbiphenyl, m.p. 51-52° (lit 52°),[126] was supplied by Professor J. I. G. Cadogan.

Preparation of 2-Arylfurans

These were prepared using the method described by Johnson[154] which is exemplified by the synthesis of 2-(4-t-butylphenyl)furan:-

N-Nitroso-4-t-butylacetanilide (2.2 g, 10 mmol) was dissolved in furan (23.5 g, 350 mmol) and stirred at room temperature for 16 h; the solution was then heated at its b.p. for a further 3 h and allowed to cool. Ether (25 ml) was added and the solution was washed with saturated aqueous sodium hydrogen carbonate solution (2 x 25 ml) and water (25 ml) and dried over anhydrous magnesium sulphate.

The low boiling liquids were removed by evaporation and the crude residue (1.2 g) was distilled to give 2-(4-t-butylphenyl)furan (0.92 g, 46%) at 72°/0.4 mmHg (lit 56°/0.04 mmHg);[150] i.r. and n.m.r. spectra were as reported.[150]

Other 2-arylfurans prepared by this method were:-

2-(4-chlorophenyl)furan	m.p. 74-75° (lit 74-75°)[154]
2-(4-methoxyphenyl)furan	m.p. 51-52° (lit 51.5°)[155]
2-(4-methylphenyl)furan	b.p. 60°/0.5 mmHg (lit 56°/0.5 mmHg)[15

Preparation of Arylacetates

Using the method described by Chattaway[156] the following aryl acetates were prepared:-

4-methoxyphenylacetate	m.p. 33-34° (lit 31-32°)[151]
4-methylphenylacetate	b.p. 99°/16 mmHg (lit 212-213°)[151]
2-thioacetoxyacetanilide	m.p. 111-112° (lit 135°)[151]

A sample of 4-t-butylphenylacetate, b.p. 135°/16 mmHg (lit 246°)[151] was supplied by Professor J. I. G. Cadogan.

Preparation of Compounds Used as Benzyne Promoters

a) 1,1-Diphenylethene.

This was prepared by the reaction of phenylmagnesium bromide with ethyl acetate as described by Allen.[157]

Fractionation on a spinning band distillation apparatus was necessary to obtain a product showing less than 1% impurity by g.l.c., b.p. 36°/0.5 mmHg, (lit 113°/2 mmHg).[157]

b) 1,1-(Bis-4-biphenylyl)ethene

This was prepared by the reaction of 4-biphenylylmagnesium bromide with ethyl acetate as described by Petrov.[158] The product, m.p. 209-211° (lit 211°)[158] was recrystallised from xylene.

c) 1,1-Dibenzoylethene

This was prepared by the base catalysed condensation of formaldehyde (37.3% formalin solution) with dibenzoylmethane, as described by Cannon.[159] Ths product m.p. 178-179°, (lit 178-179°)[159] was recrystallised from ethanol.

d) Dibenzofulvene

This was prepared from 9-chloro-9-methylfluorene using the method described by Schlubach and Faltings,[160] with the addition of a chromatography stage as described by Kice[161] to give the product, m.p. 53° (lit 53°).[161]

Synthesis of 6-Methoxy-1,4-dihydronaphthalen-1,4-endoxide

a) 4-Bromo-3-nitroanisole

This was prepared according to the method described by Hodgson,[162] in which 4-amino-3-nitroanisole was diazotised in aqueous solution and the resulting diazonium sulphate was added to boiling aqueous cuprous bromide. A crude product was isolated by steam distillation and this was crystallised from ethanol to give 4-bromo-3-nitroanisole, m.p. 30-32° (lit 32°)[162] as yellow needles.

b) 3-Amino-4-bromoanisole

This was prepared according to the method described by Hodgson,[162] in which 4-bromo-3-nitroanisole was reduced by boiling in aqueous solution with iron powder and concentrated hydrochloric acid. A crude

product was obtained by steam distillation and was purified by chromatography and isolated as 3-amino-4-bromoanisole hydrochloride m.p. 182-183° (lit 186°).[162]

c) 2-Bromo-5-methoxybenzenediazonium tetrafluoroborate.

3-Amino-4-bromoanisole hydrochloride (10.4 g, 0.044 mol) was dissolved in a solution of concentrated hydrochloric acid (7.5 ml, 32% w/v) and water (11 ml), cooled to 0°, and diazotised with a solution of sodium nitrite (3.2 g, 0.048 mol) in water (6.6 ml) maintaining the reaction temperature below 5°.

A solution of sodium tetrafluoroborate (6.25 g, 0.058 mol) in water (13 ml) was cooled to 0° and added slowly to the cold stirred diazonium solution, maintaining the reaction mixture below 5°, and stirring continued for a further 10 min after addition was complete. The product was filtered off and washed with cold water (3 ml) methanol (1.5 ml) and ether (5 ml) and dried overnight under vacuum.

2-Bromo-5-methoxybenzenediazonium tetrafluoroborate (12.7 g, 96%), m.p. 136°, decomp, was obtained as a cream coloured powder. This is a new compound, analysis (Found: C, 28.2; H, 2.1; N, 9.3. $C_7H_6BBrF_4N_2O$ requires C, 28.0; H, 2.0; N, 9.3%), i.r. (nujol mull): cm^{-1}, 2290 (m, diazonium).

d) 4-Bromo-3-fluoroanisole

2-Bromo-5-methoxybenzenediazonium tetrafluoroborate (12 g, 0.04 mol) was thermolysed using the standard technique for Schiemann reactions.[163] The volatile products (6.2 g) were collected by condensation and chromatographed on alumina with petrol -2% ether; the first fraction to be eluted was distilled to give 4-bromo-3-fluoroanisole (4.2 g, 51%), b.p. 110-112°/760 mmHg, (lit 110°/760 mmHg)[164] as a colourless liquid.

e) 6-Methoxy-1,4-dihydronaphthalen-1,4-endoxide

4-Bromo-3-fluoroanisole (3.1 g, 15 mmol) in dry THF (5 ml) was added to a stirred solution of dry furan (15 ml) and dry THF (10

ml), containing magnesium turnings (0.7 g, 30 mmol), at such a rate as to maintain a steady reaction as indicated by the boiling of the furan. After subsidence of the reaction the mixture was stirred for a further 1 h and then added to water (30 ml), extracted with ether and the extracts dried over anhydrous magnesium sulphate.

The solvents were removed to give a liquid (2.4 g) which was chromatographed on alumina (120 g, 400 x 20 mm column) eluting with 1:2 petrol:ether. The first material eluted (0.6 g) was shown on g.c. (2% CAR, 150°) to be a mixture of relatively volatile components. The next material eluted was 6-methoxy-1,4-dihydronaphthalen-1,4-endoxide (0.86 g, 33%) m.p. 64-66°, M^+ 174 by g.c.-m.s. (2% CAR, 150°). Recrystallisation from cyclohexane gave a constant m.p. of 66-67°. This is a new compound; analysis (Found: C, 75.5; H, 5.8. $C_{11}H_{10}O_2$ requires C, 75.8; H, 5.8%).

N.m.r. ($CDCl_3$): δ 3.72 (s, 3H, OMe); 5.63 (broad s, 2H, bridgehead); 6.39 (d of d, 1H, aromatic); 6.88 (d, 1H, aromatic); 6.98 (broad s, 2H, olefinic); 7.10 (d, 1H, aromatic).

I.r. (nujol mull): cm^{-1}, 1628 (m, olefinic); 1600 (m, aromatic); 1092 (s, methyl ether); 1026, 992 (s, cyclic ether); 867, 850, 828, 811 (s, aromatic).

Synthesis of 4-t-Butylacetanilide

a) 4-t-Butylnitrobenzene

This was prepared using the method described by Nelson and Brown[165] in which t-butylbenzene was reacted with a mixture of nitric acid and sulphuric acid. Redistillation of the initially obtained isomer mixture through a spinning band column yielded 4-t-butylnitrobenzene as a residue after the distillation of the 2- and 3-isomers. Crystallisation from ethanol at -40° gave 4-t-butylnitrobenzene m.p. 27°, (lit 28°)[165] as colourless crystals.

b) 4-t-Butylaniline

Reduction of 4-t-butylnitrobenzene was effected using the method described by Harger[150] in which a mixture of 4-t-butylnitro-

benzene, iron powder, ethanol and water was reacted with concentrated hydrochloric acid. The crude product was extracted from the mixture and purified by distillation to yield 4-t-butylaniline b. p. 134-137°/26 mmHg (lit 108-110°/8 mmHg).[150]

c) 4-t-Butylacetanilide

Acetylation of 4-t-butylaniline was effected using the method described by Harger[150] in which acetic anhydride was added to a boiling solution of the amine in acetic acid. The product was crystallised from a 6:1 benzene:petrol solution to yield 4-t-butylacetanilide m. p. 171-173°, (lit 174°).[150]

Synthesis of 2- and 4-Hydroxybenzenediazonium Chlorides

These were prepared using the method described by Vogel[166] in which an anhydrous methanolic solution of the aminophenol hydrochloride was diazotised with commercial amyl nitrite at 0°; a crude product was precipitated with ether and purification was effected by precipitation from methanolic solution in the above manner. The grey-white products were characterised by precipitation of silver chloride from methanolic aqueous silver nitrate solution, their i. r. spectra and their coupling products with alkaline β-naphthol (see 1-Arylazo-2-naphthols, below).

Synthesis of 1-Arylazo-2-naphthols

These were prepared using the method described by Vogel[166] in which an aqueous solution of the substituted benzenediazonium chloride was added to an alkaline solution of 2-naphthol maintaining the temperature below 5°.

Prepared in this way were:-

1-(2-chlorophenylazo)-2-naphthol	m. p. 168-169° (lit 167°)[167]
1-(4-chlorophenylazo)-2-naphthol	m. p. 161-162 (lit 162.5°)[168]
1-(2-hydroxyphenylazo)-2-naphthol	m. p. 195° (lit 193°)[169]
1-(4-hydroxyphenylazo)-2-naphthol	m. p. 193-194° (lit 194°)[169]

Syntheses of Acetylarylamines

a) 2-Chloroacetanilide

This was prepared by the method used for 4-t-butylacetanilide (p 61) to give 2-chloroacetanilide m. p. 87-89° (lit 87-88°).[151]

b) 2- and 4-Acetoxyacetanilide

These were prepared by the method of Hähle[171] in which the appropriate aminophenol was boiled in acetic anhydride for 0. 5 h. Obtained in this way were:-

2-acetoxyacetanilide m. p. 124-125° (lit 124. 5°)[170]

4-acetoxyacetanilide m. p. 152-153° (lit 150-151°)[171]

The syntheses of 4-t-butylacetanilide (p.61) and 2-thioacetylacetanilide (p.57) have been described separately. Acetanilide, 3-chloroacetanilide, 4-chloroacetanilide, 4-methylacetanilide and 4-methoxyacetanilide were recrystallised from available samples before use.

Miscellaneous Preparations

a) 1, 1-Diphenyl-2-(4-chlorophenyl)ethene

This was prepared using the method described by Tadros[172] in which 4-chlorobenzylmagnesium chloride was reacted with benzophenone and the carbinol product was dehydrated in the presence of an acid catalyst to give 1, 1-diphenyl-2-(4-chlorophenyl)ethane m. p. 76-77° (lit 76-77°).[172]

b) 1, 4-Benzoquinone-4-diazide

This was prepared using the method described by Kikot[173] in which an aqueous solution of 4-hydroxybenzenediazonium sulphate was reacted with excess barium carbonate and the filtered solution cooled in ice-salt to yield the diazide as a tetrahydrate; this was dried over phosphoric oxide and crystallised from benzene to yield 1, 4-benzoquinone diazide m. p. 88°, dec. (lit 91-93°, decomp)[173] as orange brown crystals.

c) 1,4-Dioxa-2,3-benzofulvalene

This was prepared essentially using the method described by Dean[174] in which 2-hydroxybenzenediazonium chloride was reacted at room temperature with anhydrous sodium carbonate; the 1,2-benzoquinone-2-diazide thus formed was extracted into p-xylene and the solution added directly to boiling p-xylene. Chromatography on alumina (Grade III) followed by recrystallisation from 5:1 60-80 petrol, benzene yielded 1,4-dioxa-2,3-benzofulvalene as yellow needles m.p. 168-170, decomp, (lit 168°).[174]

d) 1,2,3-Benzothiadiazole

This was prepared using the method described by Jacobson[175] in which an aqueous solution of 2-aminobenzenethiol hydrochloride was diazotised. The product obtained was filtered off and crystallised from ether to yield 1,2,3-benzothiadiazole m.p. 36-37° (lit 36-37°).[175]

e) Nitrosyl Chloride

This was prepared using the method described by Morton and Wilcox[176] in which hydrochloric acid was reacted with sodium nitrite. The gaseous product was passed through sodium nitrite, potassium chloride and calcium chloride towers and collected as a solid at -60°. The solid was dissolved in acetic anhydride as a 30% w/v solution and stored under anhydrous conditions at -30°.

f) 1,4-Diacetoxybenzene

This was prepared using the method of Pritchard[177] in which 1,4-hydroquinone was acetylated with acetic anhydride in the presence of a catalytic amount of sulphuric acid at room temperature to give 1,4-diacetoxybenzene m.p. 123-124° (lit 123-124°).[177]

The Effect of some Olefinic Compounds on the Radical-Ionic Balance in the Decomposition of NNA in Benzene-Furan Compared with that of 1,1-Diphenylethene.

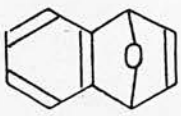
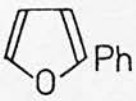
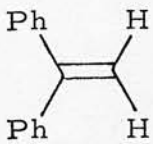
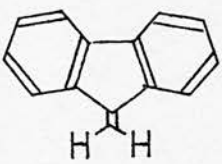
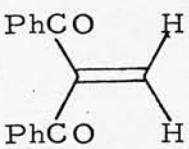
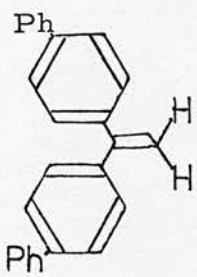
General Method

NNA (0.49 g, 3 mmol) was added to a stirred solution of the

olefin (3 mmol) in furan (3 ml, 42 mmol) and benzene (9 ml) at 60° under nitrogen and stirring continued at this temperature for a further 3 h. A naphthalene standard (0.1125 g) was added to the solution and quantitative g.c. analysis (2% CAR, 100°) was used to calculate the yields of products; confirmation of the structural assignments was obtained using g.c.-m.s.

The results are summarised in Table 3; yields are in m/100 m NNA.

Table 3

Product	PhOAc			Ph.Ph
Olefin				
	25	50	6	2
	25	48	18	1
	5	5	45	4
	17	30	36	4 †

† In this case the olefin was present as 0.3 mmol due to its low solubility.

The Decomposition of NNA in Benzene with Dibenzofulvene Present

NNA (0.36 g, 2.1 mmol) was added to a stirred solution of dibenzofulvene (0.38 g, 2.1 mmol) in benzene (6 ml) at 60° under nitrogen and heated at this temperature for 2.5 h.

Removal of the solvent gave a residue (0.56 g) which was chromatographed on alumina (50 g, 18 x 300 mm column). The only product present in identifiable quantity was a crude solid (0.055 g) which crystallised from ethanol to give a colourless crystalline material which was assigned the structure of benz(e)acephenanthrylene (0.041 g, 8 m/100 m NNA); M^+ 252. Analysis: (Found: C, 94.9; H, 4.7. Calc. for $C_{20}H_{12}$: C, 95.2; H, 4.8%). m.p. 168-169° (lit 167°).[202]

This reaction was repeated in an e.s.r. tube and the reaction observed by e.s.r. spectrometry; no hydrocarbon signal was observed at room temperature or at 30°C despite vigorous effervescence in the tube.

The Decomposition of NNA in Cumene in the Presence of Furan

NNA (0.32 g, 2 mmol) was added to a stirred solution of furan (2 ml, 28 mmol) in cumene (6 ml) at 60° under nitrogen and heated at this temperature for 2.5 h. Naphthalene (0.07 g) was added as an internal standard and examination by g.c. (5% APL, 97° for 2 min, rising at 5°/min to 120° for benzene, and 2% CAR, 100° for other components) allowed the following yields to be claculated: benzene 23 m/100 m, phenylacetate 2.2 m/100 m, 1,4-dihydronaphthalen-1,4-endoxide 14.5 m/100 m and 2-phenylfuran 24 m/100 m NNA. Biphenyl was not observed (0.5 m/100 m NNA would have been).

Assignments were confirmed by g.c.-m.s.

The Decomposition of N-Nitrosoacylarylamines in Benzene-Furan Solution and with 1,1-Diphenylethene also Present.

N-Nitroso-4-t-butylacetanilide

N-Nitroso-4-t-butylacetanilide (3.96 g, 18 mmol) was added

to a stirred solution of 1,1-diphenylethene (3.24 g, 18 mmol) in furan (15 ml, 210 mmol) and benzene (45 ml) at 60° under nitrogen; heating at this temperature was continued for 2 h. G.c. and g.c.-m.s. (2% CAR, 124°) showed the presence of 4-t-butylphenyl acetate, 2-(4-t-butylphenyl)furan, 6-t-butyl-1,4-dihydronaphthalen-1,4-endoxide and 4-t-butylbiphenyl. Naphthalene (0.1066 g) was added to the mixture as an internal standard and the g.c. was re-recorded.

The solvents were removed from the mixture and the residue (8 g) was chromatographed on alumina (400 g, 24 x 1000 mm column). Eluting with petrol the first fractions obtained were seen by g.c. (2% CAR 124°) to be mixtures of naphthalene and the previously observed products, except for the endoxide which was not present. With 1% ether in petrol the next materials to be eluted were identified by g.c.-m.s. (2% CAR, 220°) as a 1:5 mixture of 1,1-diphenyl-2-(4-t-butylphenyl)ethane and 1,1-diphenyl-2-(4-t-butylphenyl)ethene; addition of fluoranthene (0.3408 g) to these combined fractions as an internal g.c. standard showed the yield of 1,1-diphenyl-2-(4-t-butylphenyl)-ethene to be 8% by g.c. (2% CAR, 220°).

At 10% ether in petrol a substance was eluted which was identified as 1,1-diphenyl-2-(4-t-butylphenyl)ethyl acetate (0.38 g, 6%). This is a new compound; analysis (Found: C, 83.9; H, 7.5. $C_{26}H_{28}O_2$ requires C, 83.9; H, 7.5%). Recrystallisation from cyclohexane gave constant m.p. 120-121°. N.m.r. ($CDCl_3$): δ, 1.28 (s, 9H, Bu^t); 2.08 (s, 3H, acetoxy); 4.05 (s, 2H, benzylic); 6.86 and 7.1 (d of d and s, 14H, aromatic) i.r., (ν): cm^{-1}, 1740 (s, C=O); M^+ 372.

At 25% ether in petrol a compound was eluted which was identified as 6-t-butyl-1,4-dihydronaphthalen-1,4-endoxide (0.8065 g, 22.5%) b.p. 78°/0.1 mmHg (lit 83-84°/0.04 mmHg). M^+ 200; i.r. and n.m.r. identical with reported data.[150]

No significant amount of any other material was isolated from the column.

From the g.c. previously recorded the yields of the following were calculated:-

4-t-butylphenylacetate 13%

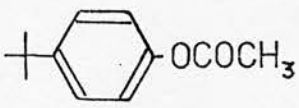
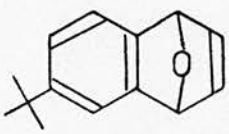
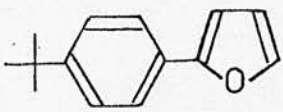
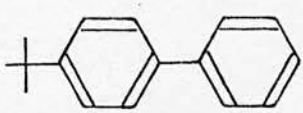
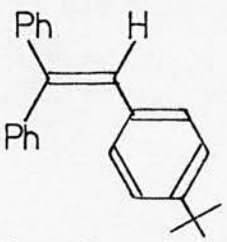
2-(4-t-butylphenyl)furan 10%

6-t-butyl-1,4-dihydronaphthalen-1,4-endoxide 31%

4-t-butylbiphenyl 2%.

The above experiment was repeated on a smaller scale without 1,1-diphenylethene being present. The yields of compounds identified as being present by g.c. (2% CAR 125°) are tabulated alongside those for the 1,1-diphenylethene experiment (Table 4).

Table 4

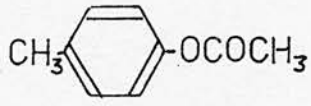
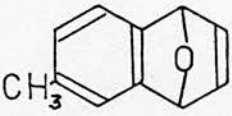
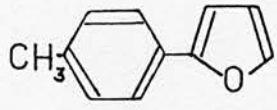
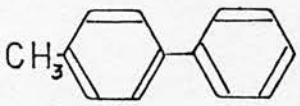
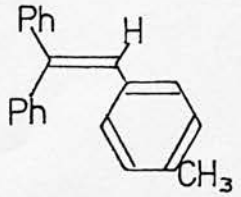
Reaction medium	Benzene + furan	Benzene + Furan + 1,1-Diphenylethane
Product		
	1.5	13 %
	3	31 %
	58	10 %
	13	2 %
	-	8† %

† Based on the w/w calibration of triphenylethene against fluoroanthrene.

N-Nitroso-4-methylacetanilide

N-Nitroso-4-methylacetanilide (0.356 g, 2 mmol) was added to a stirred solution of 1,1-diphenylethene (0.36 g, 2 mmol) in furan (2 ml, 28 mmol) and benzene (6 ml) at 60° under nitrogen and heating was continued at this temperature, (reaction A). A parallel reaction was run in which 1,1-diphenylethene was not present; (reaction B). After 3 h the solutions were allowed to cool; 1,4-di-t-butylbenzene (0.07 g) was added to A and B and fluoranthene was added to A, as internal standards. The yields of 4-methylphenylacetate, 2-(4-methylphenyl)furan, and 4-methylbiphenyl (10% SE 30, 140°) and 1,1-diphenyl-2-(4-methylphenyl)ethene (2% CAR, 200°) were claculated by g.c.; see Table 5 . Structures were assigned by comparing g.c. retention times with those of authentic samples and by g.c.-m.s. except for 1,1-diphenyl-2-(4-methylphenyl)ethene whose structure was assigned solely on the basis of g.c.-m.s.

Table 5

Reaction medium	Benzene + Furan (B)	Benzene + Furan + 1,1-Diphenylethene (A)
Product		
	undetected	0.4 %
	undetected	undetected %
	33	6 %
	11	1.4 %
	-	15[f] %

† Based on the w/w calibration of triphenylethene against fluoranthene.

The above reaction A was repeated on a larger scale using N-nitroso-4-methylacetanilide (2.6 g, 14.6 mmol), 1,1-diphenylethene (2.63 g, 14.6 mmol), benzene (42 ml), and furan (14 ml, 193 mmol).

After removal of the benzene and furan the tacky residue (4.8 g) was triturated with a 1:1 ether-petrol solution and this yielded a red-brown non-crystalline solid (1.1 g, m.p. 150-160°) which was filtered off; the solid could not be crystallised from any of the common organic solvents, although it was soluble in benzene and in chloroform and could be reprecipitated with petrol or ether. I.r. (nujol mull) showed medium intensity absorptions at 820 cm^{-1} and 700 cm^{-1}; n.m.r. (CCl_4) showed broad absorptions from δ 8.0 to δ 6.0 and from δ 2.6 to δ 1.7. A structure could not be assigned to this material and it was assumed to be a polymer. Analysis: (Found: C, 82.7; H, 6.3; N, 6.0%).

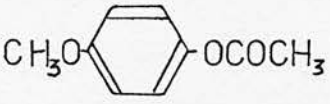
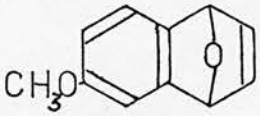
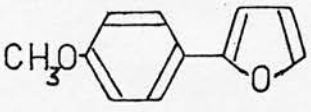
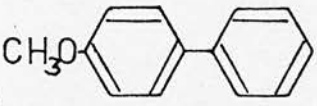
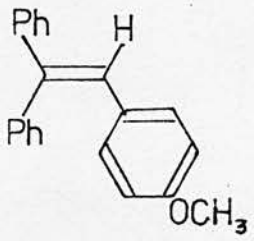
G.c. analysis (10% SE30, 150°) of the 1:1 ether-petrol solution showed the previously identified compounds and 1,1-diphenylethene to be present in the same ratios as before.

N-Nitroso-4-methoxyacetanilide

N-Nitroso-4-methoxyacetanilide (0.39 g, 2 mmol) was added to a stirred solution of 1,1-diphenylethene (0.36 g, 2 mmol) in furan (2 ml, 28 mmol) and benzene (6 ml) at 60° under nitrogen and heating continued at this temperature; (reaction A). A parallel reaction was run in which 1,1-diphenylethene was not present; (reaction B). After 3 h the solutions were allowed to cool; α-methylstilbene (0.04 g) was added to each and fluoranthene (0.1334 g) was added to A, as internal standards. The yields of 4-methoxyphenylacetate, 6-methoxy-1,4-dihydronaphthalen-1,4-endoxide, 2-(4-methoxyphenyl)furan and 4-methoxybiphenyl (2% CAR, 150°) and 1,1-diphenyl-2-(4-methoxyphenyl)-ethene (2% CAR, 220°) were calculated by g.c.; see Table 6.

Structures were assigned by comparing g.c. retention times with those of authentic samples and by g.c.-m.s. except for 1,1-diphenyl-2-(4-methoxyphenyl)ethene whose structure was assigned solely on the basis of g.c.-m.s.

Table 6

Reaction medium	Benzene + Furan (B)	Benzene + Furan + 1,1-Diphenylethene (A)
Product		
	undetected	0.6 %
	undetected	1.7 %
	50	12 %
	12	4 %
	-	21[†] %

[†] Based on the w/w calibration of triphenylethene against fluoranthene.

The above reaction A was repeated on the same scale and allowed to cool. A solution of 6-methoxy-1,4-dihydronaphthalen-1,4-endoxide (0.0308 g, 0.18 mmol) and α-methylstilbene (0.04 g) in dry benzene (3 ml) was prepared, the ratios were measured by g.c. (2% CAR, 150°), and the solution was added to the reaction mixture. The ratio of endoxide to standard was again measured by g.c. and

showed a small enhancement of the endoxide peak, the solution was re-heated for a further 3 h and g. c. examination after this period showed no diminution of the ratio of endoxide to standard; this indicates that any 6-methoxy-1, 4-dihydronaphthalen-1, 4-endoxide formed is stable under the reaction conditions.

The Decomposition of N-Nitrosoacylarylamines in Benzene and with 1, 1-Diphenylethene also Present.

N-Nitroso-2-chloroacetanilide

a) Decomposition in Benzene

N-Nitroso-2-chloroacetanilide (0.4 g, 2 mmol) was added to stirred benzene (5.5 ml) at 50° under nitrogen and the solution was heated at this temperature for 2.5 h, after which time no gas evolution was observed.

Filtration of the cooled solution yielded a solid residue (0.0027 g) which gave a positive test for ionic chloride with aqueous silver nitrate solution; the i. r. spectrum was similar to that of 2-hydroxybenzenediazonium chloride. Addition to alkaline 2-naphthol gave a red product which had the same R. f. value on t. l. c. (silica, eluting with ether) as 1-(2-hydroxyphenylazo)-2-naphthol and m. s. showed this red material to have M^+ 264. The original solid was assigned the structure 2-hydroxybenzenediazonium chloride (0.0027 g 0.9 m/100 m N-nitroso-2-chloroacetanilide).

The reaction mixture was examined by g. c. (2% CAR, 170°) and biphenyl and phenanthrene were added as standards. 2-Chlorobiphenyl (69 m/100 m 2-Cl NNA) and 2-acetoxybiphenyl (0.7 m/100 m 2-Cl NNA) were identified by g. c. retention times; the former assignment was confirmed by g. c. -m. s. while the latter, which did not give a sufficiently intense signal for g. c. -m. s. was supported by a peak of the same g. c. retention as 2-acetoxybiphenyl being observed on a different phase (3% NPGS, 210°)

Addition of aniline (0.19 g, 2 mmol) to the solution and heating

at 50° for 0.5 h gave rise to a component which was identified by g.c. retention (2% CAR, 170°) and g.c.-m.s. as acetanilide (2 m/100 m 2-Cl NNA).

b) Decomposition in Benzene and 1,1-Diphenylethene

N-Nitroso-2-chloroacetanilide (0.4 g, 2 mmol) was added to a stirred solution of 1,1-diphenylethene (0.36 g, 2 mmol) in benzene (5.5 ml) at 50° under nitrogen and maintained at this temperature for 2 h after which time no gas evolution was observed.

The precipitate which had formed in the mixture was filtered off and dried to give a buff coloured, non-crystalline solid (0.11 g); the solution was heated for a further 1 h at 50° but no further precipitation was observed.

Aqueous silver nitrate solution was added to an aqueous solution of a small portion of the precipitate; the white precipitate which formed dissolved upon the addition of concentrated aqueous ammonia but not upon the addition of concentrated nitric acid or glacial acetic acid; this indicated the presence of ionic chloride.

The i.r. spectrum of the solid showed a diazonium absorption ($2270\ cm^{-1}$) and when the solid (0.08 g) was added to alkaline 2-naphthol a red precipitate was obtained. This was purified by wet column chromatography (silica, eluting with benzene) and the product was assigned the structure 1-(2-chlorophenylazo)-2-naphthol (0.118 g), m.p. and mixed m.p. 166-168° (lit 168-169°);[167] i.r. spectrum identical to that of the authentic compound; M^+ 282/284.

The original precipitate was therefore assigned the structure 2-chlorobenzenediazonium chloride; a sample was precipitated from acetonitrile with ether and analysed (Found: C, 40.7; H, 2.3; N, 15.85. Calc. for $C_6H_4Cl_2N_2$: C, 41.2; H, 2.3; N, 16.0%). The yield of the solid precipitate was therefore 31 m/100 m 2-Cl NNA and the yield of coupling product with 2-naphthol was 91 m/100 m 2-chlorobenzenediazonium chloride.

Biphenyl (0.03 g), phenanthrene (0.0471 g) and 4-terphenyl (0.05 g) were added as standards to the original filtered reaction mixture.

2-Chlorobiphenyl (3 m/100 m 2-Cl NNA) was identified by g.c. retention time and by g.c.-m.s. (10% PEGA); and 1,1-diphenyl-2-(2-chlorophenyl)ethene (5.5. m/100 m 2-Cl NNA) was identified by g.c.-m.s. only (10% SE30, 220°) using the m.s. of the 4-chlorophenyl isomer for comparison and the calibration of this isomer against 4-terphenyl for calculating the yield.

G.c. (2% CAR, 190°) indicated the presence of 2-acetoxybipheny (0.3 m/100 m 2-Cl NNA) and 2-hydroxybiphenyl (0.5 m/100 m 2-Cl NNA); these assignments could not be confirmed by g.c.-m.s. because of their low concentrations.

This experiment was repeated and after filtering off the precipitat aniline (0.19 g, 2 mmol) was added to the filtered solution and heating was continued for a further 0.5 h at 50°. Phenanthrene standard (0.032 g) was added and g.c. and g.c.-m.s. (2% CAR, 175°) showed the presen of acetanilide (31 m/100 m 2-Cl NNA) which had not been present befor the addition of the aniline.

N-Nitroso-3-chloroacetanilide

a) Decomposition in Benzene

Nitrosyl chloride (0.53 g, 8 mmol, 30% w/v in acetic anhydride) was added over 0.5 h to a stirred solution of 3-chloroacetanilide (0.62 g, 4 mmol) in acetic acid (4 ml), acetic anhydride (2 ml) and potassium acetate (0.6 g, fused) with phosphoric oxide (0.05 g) added, while the temperature was maintained below 5°. The mixture was stirred for a further 1.5 h at this temperature and then poured onto ice-water (50 g) and stirred vigorously for 15 min. The oily product was extracted into benzene (2 x 6 ml) and the combined extracts were washed with saturated aqueous sodium hydrogen carbonate (2 x 15 ml) and water (15 ml), and dried over anhydrous magnesium sulphate for 15 min.

The dried benzene solution was filtered and heated at 50° under nitrogen for 2.5 h; no precipitation was observed. Biphenyl (0.1398 g) and phenanthrene (0.1 g) were added as standards and 3-chlorobiphenyl (63 m/100 m 3-chloroacetanilide) was shown to be present by g.c.

retention time and g.c.-m.s. (10% SE30, 160° and 2% CAR, 180°). Aniline (0.55 g, 6 mmol) was added to the solution and it was heated at 50° for a further 0.5 h; acetanilide (113 m/100 m 3-chloroacetanilide was shown to be present by g.c. retention time and g.c.-m.s. (2% CAR, 180°); this was assumed to be derived from acetic anhydride from the original reaction in which the N-nitroso-3-chloroacetanilide was synthesised.

b) Decomposition in Benzene and 1,1-Diphenylethene

The N-nitroso-3-chloroacetanilide oil was synthesised from 3-chloroacetanilide (0.62 g, 4 mmol) as described in part a), it was extracted into benzene (2 x 6 ml) in which was dissolved 1,1-diphenylethene (0.72 g, 4 mmol) and this solution was washed and dried as in a). After filtration the solution was heated at 50° under nitrogen for 2.5 h; no precipitation was observed.

Biphenyl (0.111 g), phenanthrene (0.1 g) and 4-terphenyl (0.05 g) were added as standards and 3-chlorobiphenyl (14 m/100 m 3-chloroacetanilide) was shown to be present by g.c. retention time and g.c.-m.s. (10% SE30, 160° and 2% CAR 180°); 1,1-diphenyl-2-(3-chlorophenyl)ethene (30 m/100 m 3-chloroacetanilide) was identified by g.c.-m.s. only (2.5% SE30, 190°), using the m.s. of the 4-chlorophenyl isomer for comparison, and the calibration of this isomer against 4-terphenyl for calculating the yield.

Aniline (0.55 g, 6 mmol) was added to the solution and it was heated at 50° for a further 0.5 h; acetanilide (106 m/100 m 3-chloroacetanilide) was shown to be present by g.c. retention time and g.c.-m.s (2% CAR, 180°); this was assumed to be derived from acetic anhydride from the original reaction in which the N-nitroso-3-chloroacetanilide was synthesised.

N-Nitroso-4-chloroacetanilide

a) Decomposition in Benzene

N-Nitroso-4-chloroacetanilide (0.44 g, 2.2 mmol) was added

to stirred benzene under nitrogen at 50° and maintained at this temperature for 3 h. Filtration of the reaction mixture gave 4-hydroxybenzenediazonium chloride (0.014 g, 3.7 m/100 m 4-Cl NNA); this gave a white precipitate with aqueous silver nitrate solution which would dissolve in concentrated aqueous ammonia but not in concentrated nitric acid or glacial acetic acid, indicating the presence of ionic chloride. The filtrate had an i.r. spectrum identical with that of authentic 4-hydroxybenzenediazonium chloride and when 0.01 g was coupled with aqueous alkaline 2-naphthol a red solid was obtained which was chromatographed (silica wet column, eluting with ether) to give 1-(4-hydroxyphenylazo)-2-naphthol (0.008 g) m.p. and mixed m.p. 192-194° (lit 194°).[169]

Phenanthrene (0.0252 g) was added to the filtered reaction mixture as a standard; after g.c. examination (3% NPGS, 195°) aniline (0.25 g, 3 mmol) was added and the solution was heated at 50° for a further 1 h. Re-examination by g.c. indicated the presence of acetanilide (6 m/100 m 4-Cl NNA), not previously present. Addition of further phenanthrene (0.1690 g) allowed the yield of 4-chlorobiphenyl (68 m/100 m 4-Cl NNA) to be calculated. The above assignments were made on the basis of g.c. retention times and confirmed by g.c.-m.s.

b) Decomposition in Benzene and 1,1-Diphenylethene

(i) N-Nitroso-4-chloroacetanilide (0.374 g, 1.88 mmol) was added to a stirred solution of 1,1-diphenylethene (0.34 g, 1.88 mmol) in benzene (6 ml) at 50° under nitrogen and maintained at this temperature for 3 h. The precipitate of 4-hydroxybenzenediazonium chloride (0.079 g, 27 m/100 m 4-Cl NNA) was filtered off; this gave the same reactions with aqueous silver nitrate as had been observed in part a) indicating the presence of ionic chloride; the i.r. spectrum was identical to that of authentic 4-hydroxybenzenediazonium chloride. Precipitation of the solid from ethanol solution with ether gave a white non-crystalline solid, i.r. spectrum the same as previously observed; n.m.r. $[(CD_3)_2SO_2]$ δ: 7.35 (d, 2H); 8.58 (d, 2H); 10.7 (broad s,

1H). Analysis (Found: C, 45.2; H, 3.05; N, 17.5. Calc. for $C_6H_5ClN_2O$: C, 46.05; H, 3.2; N, 17.9%).

Coupling of the solid with alkaline 2-naphthol and crystallisation from ethanol gave 1-(4-hydroxyphenylazo)-2-naphthol m.p. 193-194° (lit 194°).[169] Analysis (Found: C, 72.8; H, 4.6; N, 10.5. Calc for $C_{16}H_{12}N_2O_2$: C, 72.7; H, 4.6; N, 10.5%).

Phenanthrene (0.1086 g) and 4-terphenyl (0.0392 g) were added to the filtered reaction mixture as standards; g.c. examination (3% NPGS 195° and 220°) showed 4-chlorobiphenyl (6 m/100 m 4-Cl NNA) and 1,1-diphenyl-2-(4-chlorophenyl)ethene (9 m/100 m 4-Cl NNA) to be present. Aniline (0.25 g, 3 mmol) was added and the mixture was heated at 50° for a further 1 h. G.c. (3% NPGS, 195°) now showed the presence of acetanilide (31 m/100 m 4-Cl NNA) not previously present. All of the above compounds were identified by g.c. retention times and g.c.-m.s.

The presence of 4-acetoxybiphenyl (0.3 m/100 m 4-Cl NNA) was indicated on g.c. (3% NPGS, 195°) by a signal having the same retention time as an authentic sample but this was too weak to confirm by g.c.-m.s.

(ii) N-Nitroso-4-chloroacetanilide (0.397 g, 2 mmol), 1,1-diphenylethene (0.36 g, 2 mmol) and benzene were reacted as described above [b(i)]. The solid products from the reaction were filtered off, washed with dry benzene (5 ml) and dissolved in ice-cold water (30 ml); this solution was added slowly to a solution of 2-naphthol (0.43 g, 3 mmol) and sodium hydroxide (0.16 g, 4 mmol) in ice-water (20 ml) and stirred for 3 h, allowing the mixture to come to room temperature; it was acidified with dilute hydrochloric acid and the water-insoluble dark red products were extracted into ether. 3-Nitroaniline standard (0.1140 g) was added to the solution and examination by h.s.l.c. (Sphensorb S.10W silica, 10% EtOAc in hexane) showed components with identical R.f. values to 1-(4-hydroxyphenylazo)-2-naphthol (15 m/100 m 4-Cl NNA) and 1-(4-chlorophenylazo)-2-naphthol (1 m/100 m 4-Cl NNA).

Blank experiments in which authentic 4-hydroxybenzenediazonium

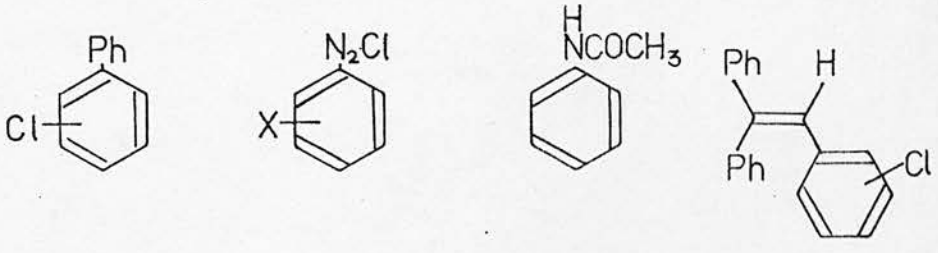
chloride was reacted under the above conditions yielded 1-(4-hydroxyphenylazo)-2-naphthol (50 m/100 m 4-hydroxybenzenediazonium chloride) as measured by h. s. l. c. (Spherisorb S. 10W silica, 10% EtOAc in hexane).

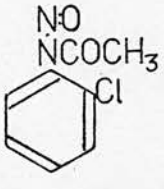
(iii) In a separate experiment 1, 1-diphenyl-2-(4-chlorophenyl)-ethene was isolated in 8% yield by chromatography of the reaction mixture on alumina, eluting with petrol-2% ether; this was identified by m. p. and mixed m. p. 75-76° (lit 76-77°)[172] and i. r. spectrum identical to that of an authentic sample. Analysis (Found: C, 82.6; H, 5.0. Calc for $C_{20}H_{15}Cl$: C, 82.6; H, 5.2%).

The yields of the major products from the decompositions of the 2-, 3-, and 4-chloro substituted N-nitrosoacetanilides are tabulated (Table 7).

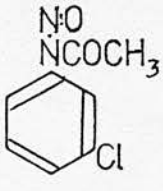
Table 7

Reactions at 50° of N-Nitroso-chloroacetanilides in Benzene (A) and in Benzene and 1, 1-Diphenylethene (B)





A	69 (2-Cl)	0.9 (X=2-OH)	2		
B	3 (2-Cl)	31 (X=2-Cl)	31	5.5 (2-Cl)	



A	63 (3-Cl)	not observed	(111)†	
B	14 (3-Cl)	not observed	(106)†	30 (3-Cl)

A	68 (4-Cl)	3.7 (X=4-OH)	6		
B	6 (4-Cl)	31 (X=4-OH)	31	9 (4-Cl)	

Yields are expressed as m/100 m N-nitrosochloroacetanilide in the 2- and 4-chloro cases and m/100 m 3-chloroacetanilide in the 3-chloro case.

/ Contamination from previous experimental stage.

N-Nitroso-2-acetoxyacetanilide

a) Decomposition in Benzene

N-Nitroso-2-acetoxyacetanilide (0.444 g, 2 mmol) was added to boiling benzene (6 ml) under nitrogen and heating was maintained for 3 h after which time no gas evolution was observed.

Phenanthrene standard (0.03 g) was added and g.c. retention times and g.c.-m.s. (2% CAR, 190° and 3% NPGS, 220°) showed 2-acetoxybiphenyl (13 m/100 m 2-acetoxy-NNA) and 2-hydroxybiphenyl (1.5 m/100 m 2-acetoxy NNA) to be present; no 1,4-dioxa-2,3-benzofulvalene was observed (0.5 m/100 m 2-acetoxy-NNA would have been observed).

Aniline (0.19 g, 2 mmol) was added and the solution was heated at 50° for 0.5 h; acetanilide (27 m/100 m 2-acetoxy NNA) not previously present, was identified by g.c. and g.c.-m.s. (2% CAR, 175°) while the ratio of 2-acetoxybiphenyl to phenanthrene remained constant.

b) Decomposition in Benzene and 1, 1-Diphenylethene

The above experiment a) was repeated with the addition of 1, 1-diphenylethene (0. 36 g, 2 mmol) to the benzene (6 ml) before the addition of the N-nitroso-2-acetoxyacetanilide (0.444 g, 2 mmol). 2-Acetoxybiphenyl (1. 7 m/100 m 2-acetoxy-NNA) and 2-hydroxybiphenyl (1. 1 m/100 m 2-acetoxy-NNA) were shown to be present (2% CAR, 190° and 3% NPGS 220°) and after the addition and reaction of aniline (0. 19 g, 2 mmol) acetanilide (96 m/100 m 2-acetoxy NNA) was also seen to be present (2% CAR 175°). No 1, 4-dioxa-2, 3-benzofulvalene was observed.

G. c. -m. s. (2% CAR 220°) showed peaks corresponding to two further substances; the larger had M^+ 272 and a fragmentation consistent with 2, 2-diphenyl-2, 3-dihydrobenzofuran while the smaller had M^+ 318 and a fragmentation consistent with 1, 1-diphenyl-2-(2-acetoxyphenyl)ethene.

The g. c. response of the above compounds relative to the standards present indicated low yields. In order to quantify these results two parallel experiments were run in which N-nitroso-2-acetoxyacetanilide (0. 222 g, 1 mmol) was added to boiling solutions of 1, 1-diphenylethene (0. 27 g, 1. 5 mmol) in benzene [(A, 3 ml) and (B, 11 ml)]. Reaction, as observed by gas evolution, was complete in 5 to 10 min and after 1 h triphenylethene standard (0. 03 g) was added to each solution. Assuming the w/w response of the g. c. detector to be approximately unity for triphenylethene and the M^+ 272 compound then it could be estimated that this compound was present in A as 2 m/100 m 2-acetoxy NNA and in B as 3 m/100 m 2-acetoxy NNA. Due to the apparently low yields no attempt was made to isolate this product from the reaction mixtures.

N-Nitroso-4-acetoxyacetanilide

a) Decomposition in Benzene

N-Nitroso-4-acetoxyacetanilide (0.444 g, 2 mmol) was added to stirred benzene (6 ml) under nitrogen at 50° and the mixture was

maintained at this temperature for 2 h, after which time gas evolution had ceased. Bicumyl standard (0.1 g) was added and 4-acetoxybiphenyl (50 m/100 m 4-acetoxy NNA) and 4-hydroxybiphenyl (8 m/100 m 4-acetoxy NNA) were identified by g.c. retention times and g.c.-m.s. (3% NPGS, 200° and 220°). 4-Methylaniline (0.22 g, 2 mmol) was added to the solution and after heating for a further 0.5 h at 50° 4-methylacetanilide (35 m/100 m 4-acetoxy NNA), not previously present was identified by g.c. retention and g.c.-m.s. (3% NPGS 200°)

b) Decomposition in Benzene and 1,1-Diphenylethene

(i) N-Nitroso-4-acetoxyacetanilide (0.444 g, 2 mmol) was added to a solution of 1,1-diphenylethene (0.36 g, 2 mmol) in benzene (6 ml) at 50° and maintained at this temperature under nitrogen for 2 h, after which time no gas evolution was apparent; the mixture was left stirring for 16 h at room temperature with air present and heating the solution at its b.p. after this time showed some further gas evolution.

Bicumyl (0.1 g) was added to the mixture and g.c. and g.c.-m.s. (3% NPGS, 200°) showed the presence of 4-acetoxybiphenyl (2.5 m/100 m 4-acetoxy NNA) and benzophenone (28 m/100 m 4-acetoxy NNA); 4-hydroxybiphenyl (1 m/100 m 4-acetoxy NNA) was identified by g.c. retention time only (3% NPGS, 220°).

4-Methylaniline (0.22 g, 2 mmol) was added and the solution was heated at 50° for a further 0.5 h; g.c. and g.c.-m.s. (3% NPGS, 200°) showed the presence of 4-methylacetanilide (82 m/100 m 4-acetoxy NNA) which was not previously present.

(ii) N-Nitroso-4-acetoxyacetanilide (0.444 g, 2 mmol) was added to a boiling solution of 1,1-diphenylethene (0.36 g, 2 mmol) in benzene (6 ml) and reflux was maintained for 5 h under nitrogen after which time gas evolution had completely ceased.

Bicumyl (0.1 g) was added to the solution and 4-acetoxybiphenyl (12.5 m/100 m 4-acetoxy NNA), 4-hydroxybiphenyl (4 m/100 m 4-acetoxy NNA) and benzophenone (8 m/100 m 4-acetoxy NNA) were shown to be present by g.c. and g.c.-m.s. (3% NPGS, 220°). Heating the solution in air for 5 h did not alter the amounts of these compounds present.

4-Methylaniline (0.22 g, 2 mmol) was added to the solution and after heating at 50° for 0.5 h 4-methylacetanilide (82 m/100 m 4-acetoxy NNA) was identified by g.c. (3% NPGS, 200°); this was not previously present.

(iii) N-Nitroso-4-acetoxyacetanilide (0.8 g, 3.6 mmol) was added to a boiling solution of 1,1-diphenylethene (0.65 g, 3.6 mmol) in benzene (12 ml) and reflux was maintained for 4 h under nitrogen, after which time gas evolution had ceased.

The benzene was removed to yield a black tarry residue (1.35 g). Distillation (100°/0.2 mmHg) gave a liquid (0.45 g) which was shown by g.c. (2% CAR, 200°) to be mainly diphenylethene with small amounts of benzophenone and 4-acetoxybiphenyl present. The residual solid (0.9 g) was chromatographed on silica (50 g, 16 x 400 mm column) eluting with graded mixtures of petrol and ether, and ether and methanol; 120 fractions totalling approximately 0.9 g were collected. All of the fractions were strongly coloured and g.c. (1% CAR, 200°) on the early petrol-ether eluted fractions showed 4-acetoxybiphenyl, benzophenone and 4-hydroxybiphenyl to be present but all were contaminated with tacky coloured material.

Examination of all further fractions by t.l.c. showed mixtures of small amounts of materials, all contaminated with tacky coloured material; n.m.r. on combined fractions did not indicate the presence of any major components and it was concluded that there were no other major products from the reaction other than those already identified.

N-Nitroso-2-thioacetoxyacetanilide

Decomposition in Benzene

Nitrosyl chloride (0.9 g, 16.5 mmol, 30% w/v in acetic anhydride) was added over 15 min to a stirred solution of 2-thioacetoxyacetanilide (1.71 g, 8 mmol) in acetic acid (12 ml), acetic anhydride (6 ml) and potassium acetate (2 g, fused) with phosphoric oxide (0.1 g) added while the temperature was maintained below 5°. Stirring was

continued at this temperature for 1.5 h and then the mixture was poured into a stirred ice-water slurry (400 g).

After 0.5 h the tacky oil which had formed (and had an odour similar to that of 1, 2, 3-benzothiadiazole) was extracted into benzene (150 ml), dried over anhydrous magnesium sulphate, filtered and heated under nitrogen at its b.p. under reflux for 1 h, in which time the benzene solution changed from pale to dark yellow. Naphthalene standard (0.5615 g) was added and 1, 2, 3-benzothiadiazole (100 m/100 m 2-thioacetoxyacetanilide) was calculated to be present by g.c. (2% CAR, 150°).

The benzene was then removed and the resulting yellow oil was chromatographed on an alumina dry column (200 g, Grade III; 25 x 500 mm column), eluting with petrol. Two u.v. active bands were observed and that of lower R.f. value was cut out and extracted into dichloromethane to yield crude 1, 2, 3-benzothiadiazole (0.96 g, 86 m/100 m 2-thioacetoxyacetanilide) m.p. 28-31°.

Crystallisation of the crude material from 1:1 petrol-ether gave 1, 2, 3-benzothiadiazole (0.78 g, 70 m/100 m 2-thioacetoxyacetanilide m.p. and mixed m.p. 36-37° (lit 36-37°);[175] i.r. identical to that of an authentic sample.

Decomposition of 1,4-Benzoquinone-4-diazide in Benzene and 1,1-Diphenylethene.

1,4-Benzoquinone-4-diazide (0.24 g, 2 mmol) was added to a boiling solution of 1,1-diphenylethene (0.36 g, 2 mmol) in benzene (6 ml) and reflux was maintained for 4 h under nitrogen, after which time gas evolution had ceased.

Bicumyl standard (0.1 g) was added and 4-hydroxybiphenyl (14 m/100 m diazide) and benzophenone (4 m/100 m diazide) were identified by g.c. and g.c.-m.s. (3% NPGS, 220°).

No other material was observed by g.c. (3% NPGS 220° and 1% SE30, 220°). Examination of the highly coloured reaction mixture by g.l.c. (alumina and silica with a variety of solvents) failed to

indicate the presence of any compounds not previously identified.

Decomposition of N-Nitroso-2-acetoxyacetanilide in Aromatic Solvents Other than Benzene

p-Xylene

(i) N-Nitroso-2-acetoxyacdtanilide (0.444 g, 2 mmol) in p-xylene (10 ml) was added to a boiling solution of p-xylene (15 ml) over 0.5 h and reflux was maintained under nitrogen for a further 0.5 h. Phenanthrene standard (0.05 g) was added and 1,4-dioxa-2,3-benzofulvalene (9 m/100 m 2-acetoxy NNA) was identified by g.c. retention time and g.c.-m.s. (2% CAR, 190°).

Two other major components apparent by g.c. (2% CAR 190°) were assigned as phenylacetate and 2,5-dimethyl-2'-acetoxybiphenyl on the basis of g.c.-m.s.

(ii) The above experiment (i) was repeated with the addition of 1,1-diphenylethene (0.36 g, 2 mmol) to the boiling p-xylene before the addition of the N-nitroso-2-acetoxyacetanilide solution. G.c. examination (2% CAR, 190°) after the completion of reaction showed 1,4-dioxa-2,3-benzofulvalene (9 m/100 m 2-acetoxy NNA) to be present.

(iii) N-Nitroso-2-acetoxyacetanilide (0.444 g, 2 mmol) was added in one portion to boiling p-xylene (25 ml) under nitrogen; a vigorous reaction set in immediately and after heating under reflux for a further 0.5 h phenanthrene (0.05 g) was added and 1,4-dioxa-2,3-benzofulvalene (11 m/100 m 2-acetoxy NNA) was shown to be present by g.c. (2% CAR, 190°).

(iv) Using the method described in (iii) N-nitroso-2-acetoxyacetanilide (2.4 g, 10.8 mmol) was reacted with p-xylene (130 ml). After removal of p-xylene the black tarry residue (2.2 g) was chromatographed on alumina (110 g, Grade III), eluting with benzene. The first (yellow) fraction (0.3 g) was shown by g.c. to be a mixture of 1,4-dioxa-2,3-benzofulvalene and the compound assigned as 2,5-dimethyl-2'-

acetoxybiphenyl. Rechromatography of the mixture on silica, eluting with benzene yielded crude 1,4-dioxa-2,3-benzofulvalene (0.11 g). Crystallisation from 5:1 60-80 petrol and benzene gave 1,4-dioxa-2,3-benzofulvalene (0.09 g, 10 m/100 m 2-acetoxy NNA) as yellow needles; m.p. and mixed m.p. 167° (dec) (lit 168°);[174] i.r. spectrum identical to that of an authentic sample.

Cumene

N-Nitroso-2-acetoxyacetanilide (0.222 g, 1 mmol) in cumene (6 ml) was added to boiling cumene (9 ml) over 0.5 h and reflux was maintained under nitrogen for 2 h. Phenanthrene standard (0.0262 g) was added and 1,4-dioxa-2,3-benzofulvalene (8 m/100 m 2-acetoxy NNA) was shown to be present by g.c. and g.c.-m.s. (2% CAR, 190°).

Decomposition of N-Nitroso-2-chloroacetanilide in p-Xylene

N-Nitroso-2-chloroacetanilide (0.397 g, 2 mmol) was heated in p-xylene (5 ml) at 50° under nitrogen for 2 h. The solid precipitate of 2-chlorobenzenediazonium chloride (0.05 g, 14 m/100 m 2-chloro NNA) was filtered off and characterised by its i.r. spectrum and its coupling product with 2-naphthol, 1-(2-chlorophenylazo)-2-naphthol m.p. and mixed m.p. 167-169° (lit 167°).[167]

The filtrate was immediately added in one portion to boiling p-xylene (25 ml) under nitrogen; reaction was immediate and after 5 min phenanthrene (0.0321 g) was added to the solution and it was examined by g.c. (2% CAR, 190°); no 1,4-dioxa-2,3-benzofulvalene was observed (0.5 m/100 m 2-chloro NNA would have been).

Preparation of Symmetrical Diaroyl Peroxides

These were prepared by the method described by Hey and Walker[178] which is exemplified by the case of bis-2-chlorobenzoyl peroxide:-

Thionyl chloride (40 ml, 0.5 mol) and 2-chlorobenzoic acid (15.6 g, 0.1 mol) were boiled under reflux in the absence of moisture for 20 h. Excess thionyl chloride was distilled off at 80° and the residue was distilled at 110°/15 mmHg to give 2-chlorobenzoylchloride (16 g; 91%; lit b.p.[151] 110°/15 mm).

A solution of the acid chloride (16.0 g) in chloroform (30 ml) was added over 30 min to a stirred solution of hydrogen peroxide (6% w/v, 50 ml) and aqueous sodium hydroxide solution (25% w/v, 20 ml) at 0°, maintaining the temperature below 10°. Stirring was continued for 1 h and then the solution was concentrated to approximately 30 ml.

Addition of methanol to the concentrated solution precipitated bis-2-chlorobenzoyl peroxide (12.1 g, m.p. 94-95.5°). Reprecipitation of the peroxide from a saturated solution in chloroform with methanol gave bis-2-chlorobenzoyl peroxide as colourless opaque plates, (10.3 g, 67% based on acid), m.p. 99.5° decomp (lit m.p. 95°).[179] Further reprecipitation gave no change in m.p.

Attempts to recrystallise the peroxide from a boiling 1:1 benzene-cyclohexane solution as described in the literature[179] gave lower and inconsistent m.p.'s and it was observed that gas was evolved from the hot solution suggesting that the peroxide was decomposing.

Prepared in this way were:-

bis-2-chlorobenzoyl peroxide m.p. 99.5° (lit 95°)[179]
bis-4-chlorobenzoyl peroxide m.p. 137-137.5° (lit 140°)[180]
bis-3-methylbenzoyl peroxide m.p. 53-54° (lit 54°)[180]
Also supplied by Professor J. I. G. Cadogan was:-
bis-4-methylbenzoyl peroxide m.p. 136° (lit 136°)[180]

Preparation of Bis-α-methylcinnamoyl Peroxide

This was prepared by the dicyclohexylcarbodiimide method described by Green and Kazan.[181]

A solution of α-methylcinnamic acid (10.0 g, 0.062 mol) in dichloromethane (100 ml) was added dropwise to a stirred solution of dicyclohexylcarbodiimide (13.34 g, 0.0626 mol) and 95% w/v hydrogen peroxide (10.4 g, 0.31 mol) in ether (125 ml) at 0°, maintaining the temperature below 5°. Stirring and cooling was continued until completion of the reaction was indicated by the disappearance of the i.r. absorption at 2150 cm^{-1}, characteristic of dicyclohexylcarbodiimide, and the appearance of the peroxide carbonyl doublet at 1750 cm^{-1} and 1770 cm^{-1}.

The precipitated dicyclohexylurea was filtered off and slurried with dichloromethane (3 x 100 ml). The filtered extracts were combined, an equal volume of ether was added and the solution was washed successively with saturated ammonium sulphate solution (3 x 100 ml), 10% sodium carbonate solution (2 x 100 ml) and saturated sodium chloride solution (2 x 100 ml), and dried over magnesium sulphate.

The solvents were removed under reduced pressure at room temperature to yield a crude product (10.2 g). Dicyclohexylurea, the principal contaminant, was removed by adding the crude product to 50 ml ether and filtering off the insoluble dicyclohexylurea; removal of the ether at room temperature yielded the purified peroxide (5.6 g), which was twice recrystallised from boiling ether to yield bis-α-methylcinnamoyl peroxide as opaque colourless plates (4.41 g, 45%) m.p. 73-74° decomp ; (lit[182] 74-75°).

This method gives a 10% increase in yield over the only previously reported synthesis.[182]

Attempted Syntheses of Bis-cis-2, 3- and Bis-3, 3-diphenylacryloyl Peroxides.

Application of the method described above failed to yield the

required peroxides as products.

A sample of bis-cinnamoyl peroxide, prepared by the above method, was supplied by Dr. I. H. Sadler.

Synthesis of α-Methylcinnamic acid

This compound was obtained by the Perkin condensation of benzaldehyde and propionic anhydride as described by Edeleano.[183]

Synthesis of 3, 3-Diphenylacrylic acid

This was prepared from 1, 1-diphenylethene and oxalyl chloride as described by Bergmann.[184]

Reactions Involving Aryl and Styryl Radicals

The Reaction of Bis-2-chlorobenzoyl Peroxide with Dimethylacetylenedicarboxylate

Bis-2-chlorobenzoyl peroxide (1.55 g, 5 mmol) was allowed to decompose at 70° under nitrogen in dimethylacetylenedicarboxylate (DMAD) (7.1 g, 50 mmol). The reaction mixture was taken up in 25 ml benzene and washed with 5% sodium hydrogen carbonate solution (2 x 20 ml). Separation and reacidification of the aqueous portion yielded a crude acidic product (0.16 g) which upon sublimation (125°, 20mmHg) gave 2-chlorobenzoic acid (0.101 g, 13 mol/100 mol peroxide) m.p. and mixed m.p. 139-141° lit[151] 142° i.r. identical to authentic 2-chlorobenzoic acid.

The benzene and DMAD were distilled from the organic portion to yield a tarry residue (4.2 g); t.l.c. on alumina, eluting with dichloromethane, indicated the presence of a naphthalene as a fluorescent spot under u.v. light. The residue was deposited on alumina (20 g) and eluted with dichloromethane on a 600 mm x 35 mm dry column (grade III alumina); the u.v. active band was removed and extracted

with dichloromethane to yield a tacky solid (0.06 g). This was dissolved in a small amount of boiling methanol and upon cooling crystals were obtained (0.049 g) m.p. 160-164°. The mother liquors were combined with the soluble extracts from the portions of the column adjacent to the naphthalene band to yield 0.04 g of solid; rechromatography of this material gave 0.012 g of u.v. active product m.p. 159-164°. This was combined with the original product and recrystallised from methanol to yield tetramethyl 5-chloronaphthalene-1, 2, 3, 4-tetracarboxylate (0.057 g, 3 mol/100 mol bis-2-chlorobenzoyl peroxide) m.p. and mixed m.p. 163-166° (lit[144] 165-168°), m/e 394/396.

Yields of Aroic Acids from the Decomposition of Diaroyl Peroxides in DMAD and Phenylacetylene

In each case a 10:1 molar ratio of acetylene to diaroyl peroxide was used and the procedure used was that described for the isolation of 2-chlorobenzoic acid from the decomposition of bis-2-chlorobenzoyl peroxide in DMAD (above).

The acids were characterised by m.p., mixed m.p. and comparison of i.r. spectra with those of authentic samples. The results were tabulated (Table 8).

Table 8

Yields of Aroic Acids from the Decomposition of Diaroyl Peroxides in DMAD and Phenylacetylene

Reactions	X	$X.C_6H_4CO_2H$ (m/100 m)
$(X.C_6H_4CO_2)_2$	H	3
+	2-Cl	13
$CH_3O_2C.C{:}C.CO_2CH_3$	4-Cl	10
	$3\text{-}CH_3$	10
	$4\text{-}CH_3$	11

Table 8 (cont)

Reactions	X	$X.C_6H_4CO_2H$ (m/100 m)
$(X.C_6H_4CO_2)_2$ + Ph C:CH	H	90

Yields of Carbon Dioxide from the Decomposition of Diaroyl Peroxides in DMAD and Phenylacetylene

A 10 ml flask containing the peroxide (2 mmol) and the acetylene (20 mmol) was connected to a gas burette containing liquid paraffin; the system was flushed out with nitrogen and was allowed to come to equilibrium at room temperature over one to two hours. The paraffin levels were then balanced and the level noted; the prevailing temperature and atmospheric pressure were measured.

The flask was placed in an oil bath at 80° (70° in the case of bis-2-chlorobenzoyl peroxide) and the peroxide allowed to decompose over a period of 16 h. The reaction flask was then removed from the bath and the system allowed to come to equilibrium with prevailing conditions. The paraffin levels were balanced, the level noted and the temperature and pressure again measured.

The volume of CO_2 evolved was calculated by adding an allowance of 50 cc to the initial and final volume readings to allow for the additional volume of the connecting tubing and reaction flask. To determine the molar amount of carbon dioxide evolved the initial and final volumes were converted to S. T. P. in the normal manner. The molar volume of carbon dioxide at S. T. P. was taken as 22. 26 l.

Each decomposition was performed twice and the results tabulated (Table 9).

Table 9

Yields of Carbon Dioxide from the Decomposition of Diaroyl Peroxides in DMAD and Phenylacetylene

Reactions	X	CO_2 (m/100 m)	
$(X.C_6H_4CO_2)_2$ + $CH_3O_2C.C{:}C.CO_2CH_3$	H	73	71
	2-Cl	68	66
	4-Cl	57	55
	3-CH_3	64	67
	4-CH_3	61	64
$(X.C_6H_4CO_2)_2$ + $PhC{\equiv}CH$	H	17	16

The Decomposition of Dibenzoyl Peroxide in a Solution of Benzene and DMAD

A solution of dibenzoyl peroxide (1.46 g, 1.2 mmol) in DMAD (1.8 g, 1.25 mmol) and benzene (50 ml, 560 mmol) was heated at its b.p. under a nitrogen atmosphere for 16 h. The product was washed with 5% sodium hydrogen carbonate solution (2 x 25 ml) and the organic portion dried over $MgSO_4$ before removal of the benzene to yield a solid residue (2.8 g).

Examination of this residue by t.l.c. on alumina eluting with CCl_4 showed two compounds with Rf values identical to those for authentic samples of dimethyl 1, 2-diphenyl-fumarate and -maleate. The residues were deposited on alumina (15 g, grade III) and chromatographed on a 600 x 35 mm alumina dry column, eluting with CCl_4. The portion containing the fumarate and maleate was

removed and extracted with dichloromethane to yield 0.3 g of solid material. Examination of this material by g.c. (3% NPGS, 220°) showed peaks corresponding to the required fumaric and maleic esters.

Over five runs a maleate to fumarate (i.e. cis:trans) ratio of (2.7±0.1):1 was observed.

The Reaction of Dibenzoyl Peroxide with Acetonitrile

A solution of dibenzoyl peroxide (4.84 g, 20 mmol) in acetonitrile (8.9 g, 200 mmol) was heated at its b.p. overnight under a nitrogen atmosphere.

The low b.p. components were removed by distillation between 70 and 80° and shown to be a mixture of acetonitrile and benzene by g.c. and g.c.-m.s. Using n.m.r. peak areas the benzene was calculated to be present as 0.6 g (39 m/100 m dibenzoyl peroxide).

The tarry residue was taken up in ether and washed with 5% sodium carbonate solution (2 x 20 ml). Re-acidification of the aqueous portion yielded benzoic acid (0.4 g, 16 m/100 m dibenzoyl peroxide) m.p. and mixed m.p. 120-122° (lit[151] 122°), i.r. as authentic sample.

G.c. examination (OV17, 120°) of the organic portion showed one major component. Chromatography of the residue (3.1 g) obtained after the removal of the ether on a 600 x 35 mm alumina dry column, eluting with petrol yielded biphenyl (0.08 g, 5 m/100 m dibenzoyl peroxide) m.p. and mixed m.p. 69-71° (lit[151] 71°) i.r. as authentic sample.

No other identifiable material was isolated.

The Reaction of Cinnamic Acid and Lead Tetraacetate in Benzene

Cinnamic acid (3 g, 20 mmol) and lead tetraacetate (L.T.A.) (4.4 g, 10 mmol) were heated overnight in boiling benzene (20 ml). The reaction mixture was then filtered through celite and the filtrate

washed with saturated sodium hydrogen carbonate solution (2 x 20 ml); reacidification of the aqueous portion yielded cinnamic acid (0.55 g, 18 m/100 m starting material) m.p. and mixed m.p. 129-131° lit[151] 133°. G.c. examination of the organic portion (OV17, 120°) showed one principal volatile component, which had the same retention time as 1-phenylpropene. Distillation of the organic portion yielded 1-phenylpropene (0.4 g, 17 m/100 m cinnamic acid) at 120°/15 mmHg.

A small peak corresponding to stilbene was also observed on the g.c. trace but was not present in sufficient quantity to be detected by g.c.-m.s.

The Reaction of Dicinnamoyl Peroxide with DMAD

Dicinnamoyl peroxide (0.75 g, 2.5 mmol) was decomposed over 16 h in DMAD (3.5. g, 25 mmol) at 80° under a nitrogen atmosphere. Examination of the products by t.l.c. showed no u.v. active spot characteristic of the possible naphthalene ester product.

The Photolysis of Dicinnamoyl Peroxide in Benzene

Dicinnamoyl peroxide (0.2 g) was photolysed in benzene (100 ml) using a medium pressure lamp with a pyrex filter; this gave emissions at 297, 313 and 366 mμ. The reaction mixture was monitored at 1 h intervals for 6 h and again after 24 h. No stilbene was detected.

This procedure was repeated using a low pressure lamp which gave 185 and 254 mμ emissions. No stilbene was detected.

The Decomposition of Bis-α-methylcinnamoyl Peroxide in Benzene

Bis-α-methylcinnamoyl peroxide (1 g, 3 mmol) was heated in boiling benzene (30 cc, 26.4 g, 330 mmol) under a nitrogen atmosphere for 24 h. G.c. examination of the reaction mixture (3% NPGS, 220°) showed a compound with the same retention time as trans-1, 2-

diphenylpropene; further g.c. examination (3% NPGS 100°) showed compounds with retention times identical to those of cis-1-phenylpropene, trans-1-phenylpropene and indene.

The reaction mixture was washed with saturated sodium hydrogen carbonate solution (2 x 10 ml); the aqueous extracts subsequently yielded a crude acidic material upon re-acidification (0.014 g).

Most of the benzene was removed from the product mixture by evaporation at room temperature and the liquid residue (1.8 g) was chromatographed on an alumina wet column. Elution with petrol firstly yielded mixtures of cis and trans 1-phenylpropene and indene and these assignments were confirmed by g.c.-m.s. Measurement against external standards showed each of these hydrocarbons to be present as 9 m/100 m of bis-α-methylcinnamoyl peroxide.

Further elution with petrol gave the material with g.c. retention time identical to that of trans 1, 2-diphenylpropene (0.045 g); recrystallisation from ethanol gave trans 1, 2-diphenylpropene (0.032 g, 5 m/100 m bis-α-methylcinnamoyl peroxide) m.p. and mixed m.p. 80-81° (lit[151] 82°), i.r. as authentic sample.

Increasing the elutant polarity in the normal manner and monitoring the products by t.l.c. and g.c. showed a large number of products, all present in very small quantities; no further products could be isolated in identifiable quantity.

The Decomposition of Bis-α-methylcinnamoyl Peroxide in DMAD

Bis-α-methylcinnamoyl peroxide (1.61 g, 5 mmol) was heated for 16 h at 70° in DMAD (7.2 g, 50 mmol) under a nitrogen atmosphere. The solution beçame deep blue shortly after heating was commenced and remained this colour.

Examination of the products by g.l.c. on alumina eluting with benzene showed the absence of any peroxide starting material and the presence of a u.v. active fluorescent spot, characteristic of a naphthalene; a blue spot was also visible in normal light. The

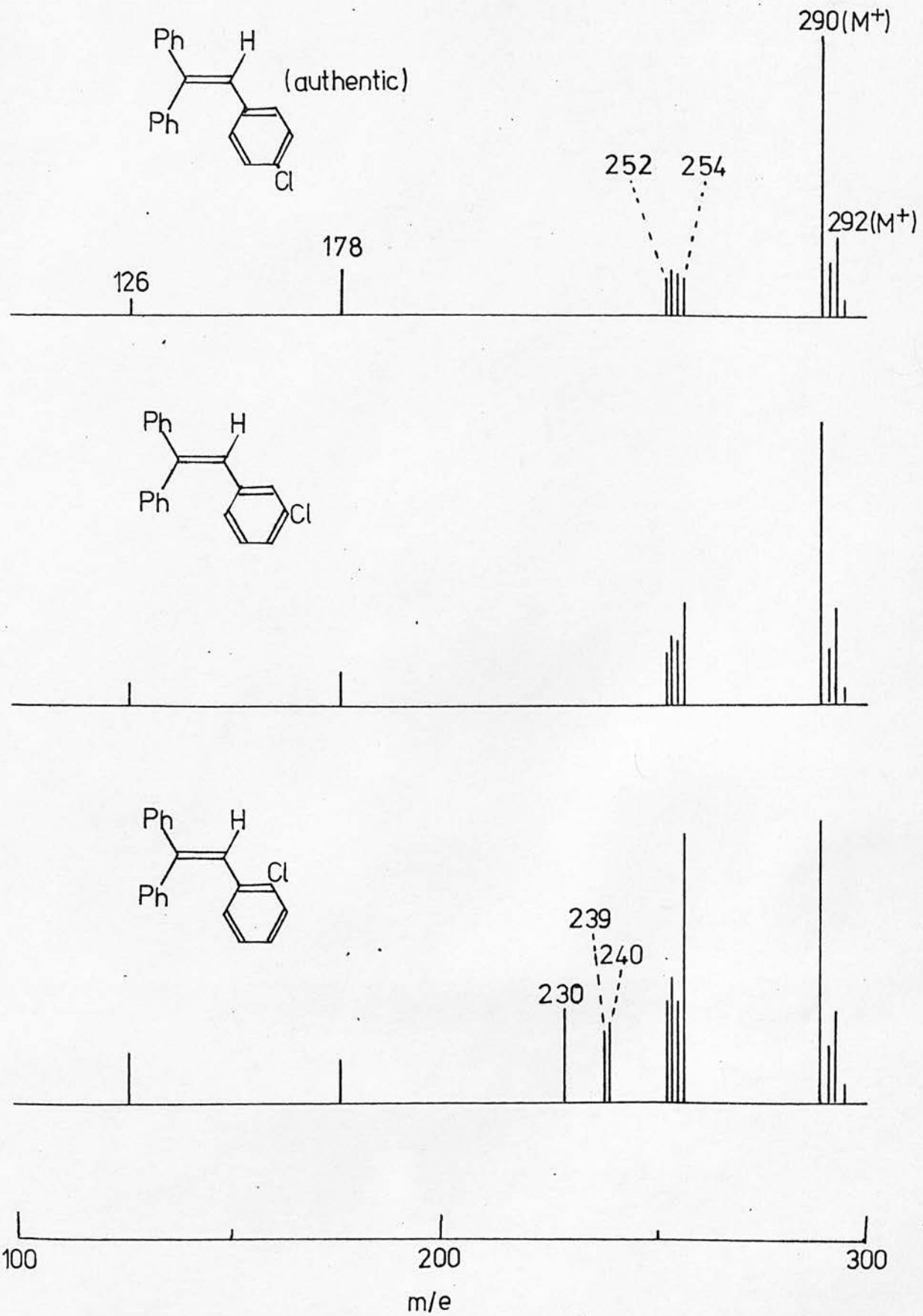
DMAD was removed by distillation to yield a tacky residue (3-4 g) which was chromatographed on an alumina dry column (32 x 750 mm), eluting with benzene. The naphthalene ester and blue material were separately extracted from the corresponding sections of the column with dichloromethane to yield 0.27 g of crude naphthalene ester and 0.42 g of crude blue material; the presence of considerable impurity in both materials was indicated by t.l.c. and n.m.r.

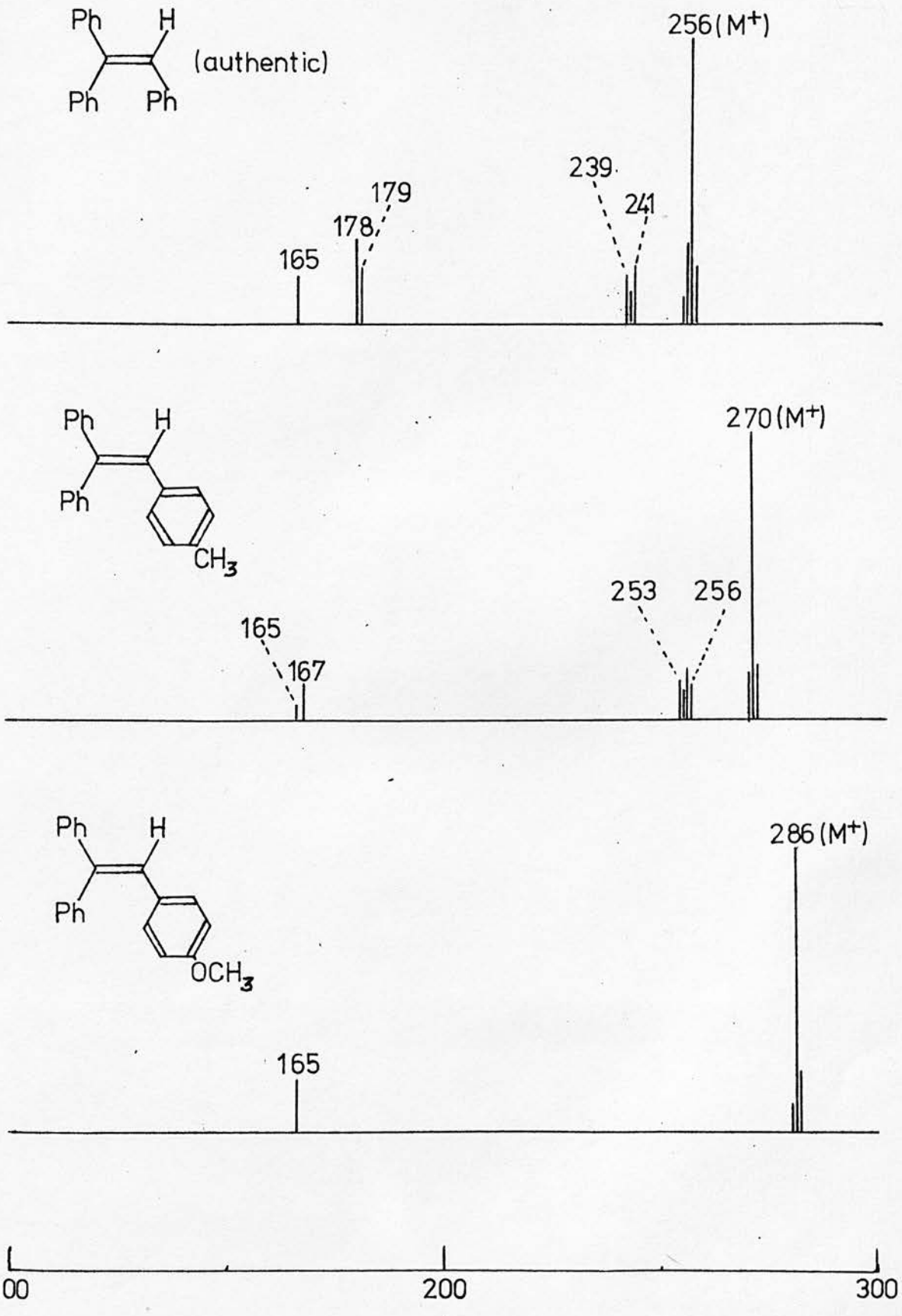
The naphthalene ester component was twice rechromatographed on alumina dry columns and distilled at $110^{\circ}/0.1$ mmHg to yield an oil (0.062 g) which was shown by g.c. (3% NPGS, 220°) to consist of one major component and a small amount of a minor component.

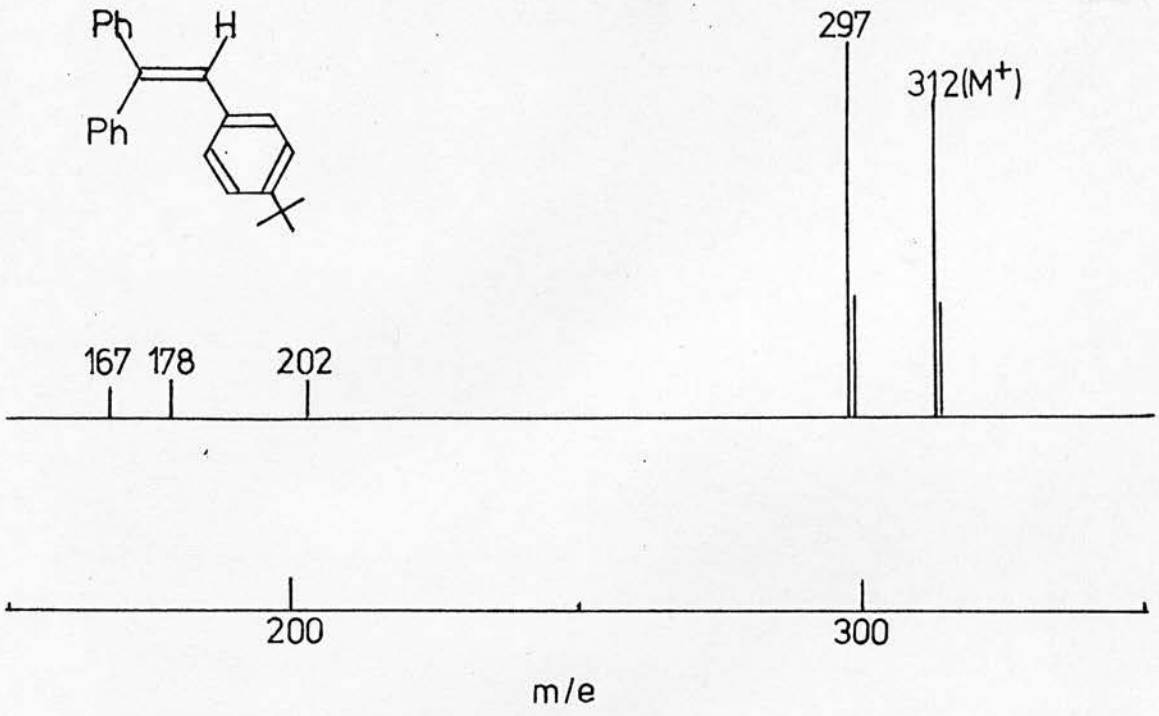
G.c.-m.s. showed the major component to be dimethyl 3-methylnaphthalene-1, 2-dicarboxylate [m/e 258 (M^+), 227 (-MeO), 199 (-CO), 168 (-MeO), and 140 (-CO); also 226 (-MeOH), 211 (-Me) and 139 ($-CO_2$, -CO)]. The n.m.r. spectrum of the mixture was also in accord with the presence of a major amount of this material: δ ($CDCl_3$) 2.52 (3H, s, Me), 3.90 (3H, s, CO_2Me), 3.95 (3H, s, CO_2Me) and 7.1-8.2 (6H, m. aromatic). The total yield was approximately 5 m/100 m peroxide.

Further attempts to purify the blue material by dry column chromatography, eluting with benzene and with carbon tetrachloride ultimately yielded a blue material (0.19 g), which was still shown to be impure by t.l.c. N.m.r. spectroscopy indicated the absence of any one major component in this mixture.

Appendix of Mass Spectra




Ph
H
Ph
Ph
(authentic)
256(M+)
239
241
179
178
165
Ph
H
Ph
CH3
270(M+)
253
256
165
167
Ph
H
Ph
OCH3
286(M+)
165
100
200
300
m/e

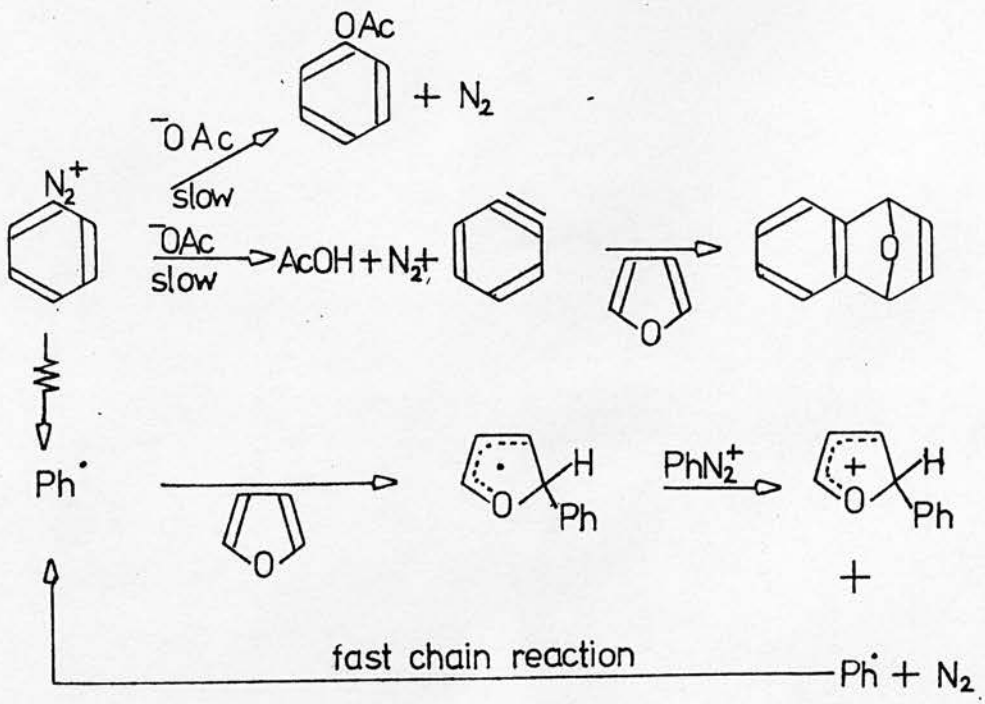

Ph
H
Ph
297
312(M+)
167
178
202
200
300
m/e

DISCUSSION CONTENTS

THE PROMOTION OF THE IONIC DECOMPOSITION OF ACETYL-ARYLNITROSAMINES

The use of alkenes to promote the formation of 1, 2-didehydrobenzene (benzyne) from N-nitrosoacetanilide (NNA) via an ionic mechanism, by suppressing the formation of phenyl radical derived products, was developed by Murray.[141] Addition of NNA to a heated solution of furan and benzene containing 1, 1-diphenylethene as aryne promoter gave a seven-fold increase in the yield of 1, 4-dihydronaphthalen-1, 4-endoxide, the adduct of benzyne with furan, over the same system with no alkene promoter present. A similar order of increase in the yield of phenyl acetate was observed; this is a product of heterolytic origin, probably formed by bimolecular displacement of nitrogen from the benzenediazonium cation by an acetate ion, although a mechanism involving unimolecular dediazonisation of the benzenediazonium cation to give a phenyl cation which adds to acetate cannot be totally dismissed, since phenyl cations can be formed in this manner.[185]

The generally accepted mechanism[129] for the decomposition of NNA in the presence of furan is shown (Scheme 18)



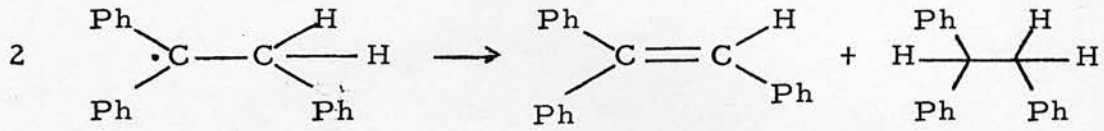
Scheme 18

The mechanism of the reaction of NNA with benzene to give biphenyl is analogous; benzene was used as a co-solvent with furan in order to allow the reaction to be carried out at 60°, a temperature higher than the boiling-point of furan, because Murray had observed that an increase in temperature increased the yields of products of ionic reaction.

Investigations into the Mechanism of Benzyne Promotion by Alkenes

Murray suggested two separate mechanisms by which alkenes might be acting as benzyne promoters. The alkene could trap chain carrying phenyl radicals more efficiently than furan to give a delocalised adduct radical (17) which would react with a further adduct radical with disproportionation to yield two neutral molecules (Scheme 19).

(17)



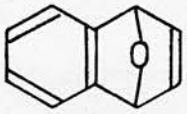
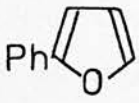
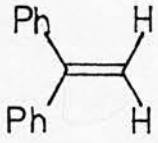
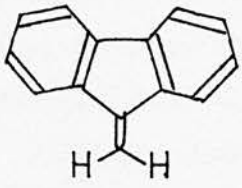
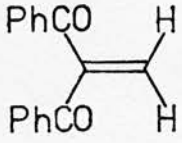
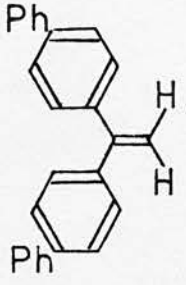
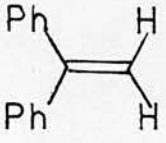
Scheme 19

If this is the major effect of alkenes in benzyne promotion then the efficiency of the promoter will be solely based upon its efficiency as a phenyl radical trap compared with furan, since addition of phenyl radicals to the promoter ultimately results in the formation of two neutral non radical species, and thus chain termination.

If however the major mode of action of the promoter is to trap chain carrying phenyl radicals and incorporate them in a slower chain process then the promoter efficiency will depend upon both its ability to efficiently trap phenyl radicals in competition with furan and of the resistance of the intermediate adduct radical to oxidation by PhN_2^+ (Scheme 20).

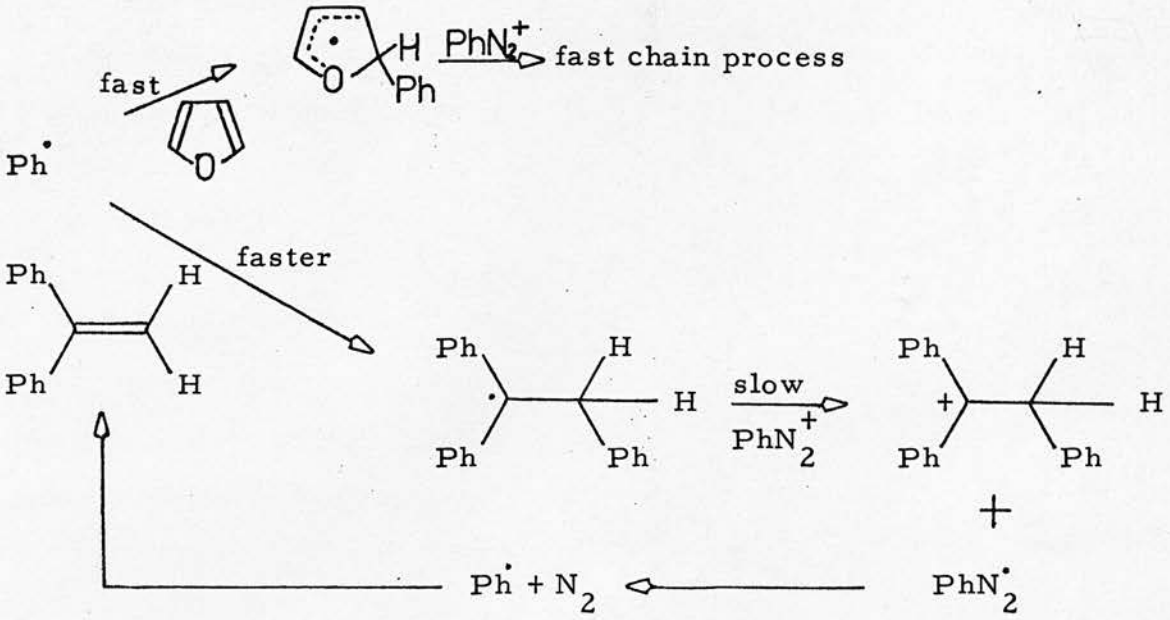
Table 3(b)

Investigations into the Mechanism of Benzyne Formation by Alkenes

Product	PhOAc			Ph.Ph
	25	50	6	2
	25	48	18	1
	5	5	45	4
† 	17	30	36	4
† 	17	29	15	4

Yields in m/100 m NNA

† In these cases the olefin was present at 0.1 m/m NNA.



slow chain process

Scheme 20

Efficient trapping followed by facile oxidation of the adduct radical would constitute a poor promoting effect since this process would also rapidly remove the PhN_2^+ benzyne precursor from solution.

As part of the investigation undertaken here alkenes with pronounced substituent characteristics were examined as adducts in the standard benzene, furan and NNA system in order to obtain a clearer insight into the mechanism of promotion; the results are tabulated against those obtained for the 1, 1-diphenylethene systems used by Murray (Table 3(b)).

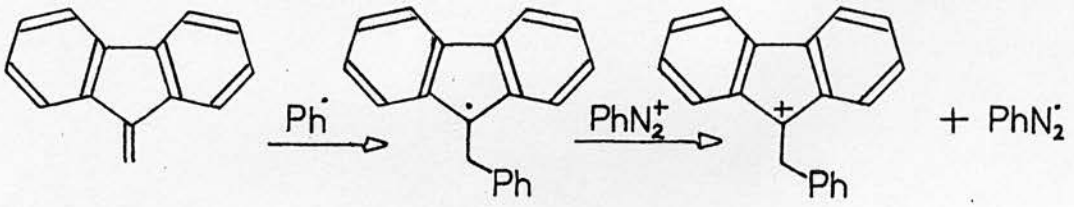
Dibenzofulvene was used as a promoter in order to determine whether or not co-planarity of the two rings into which the radical centre can be assumed to be delocalised in the phenyl radical adduct would increase the promoter effect by allowing greater delocalisation than would be possible in 1, 1-diphenylethene where co-planarity of both phenyl rings and the olefinic double bond is sterically unfavourable.

Support for the use of dibenzofulvene came from Kice's[161] estimate that this compound captures methylmethacrylate radicals two hundred times as quickly as styrene and fifty times as quickly as 1, 1-

diphenylethene; it is not unreasonable to assume that relative affinities for phenyl radicals would be of the same order.

The yields of benzyne derived 1,4-dihydronaphthalen-1,4-endoxide (48 m/100 m NNA) and of phenyl acetate (25 m/100 m NNA) using dibenzofulvene as promoter were approximately the same as those obtained using 1,1-diphenylethene, indicating that neither the reactivity towards phenyl radicals nor the ability of the radical-promoter adduct to delocalise the unpaired electron are limiting factors in the use of 1,1-diphenylethene.

In order to try to obtain further information about the intermediate phenyl radical-dibenzofulvene adduct, the reaction of NNA with a benzene solution of dibenzofulvene was examined by e.s.r. spectroscopy. The failure to observe a hydrocarbon e.s.r. signal suggested that the adduct species was not present in a high enough stationary state concentration to be detected by e.s.r.; this in turn suggests that oxidation of the adduct radical to the cation (18) is rapid (Scheme 21).



(18)

Scheme 21

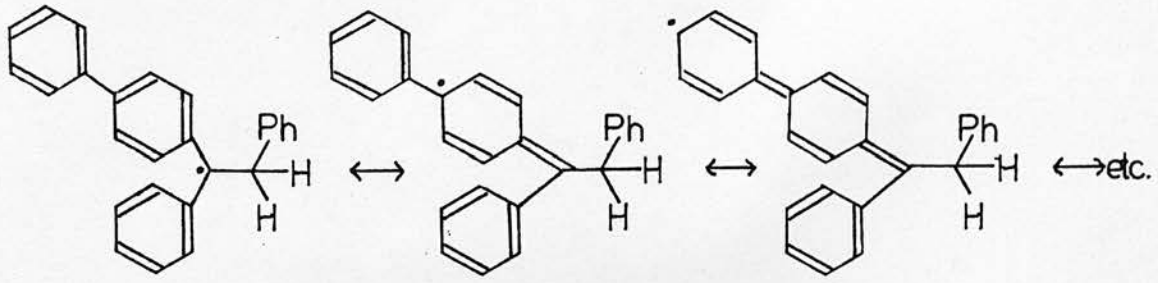
Since the cation (18) is also a highly delocalised species there is no obvious thermodynamic impediment to the oxidation step and so the oxidation appears to proceed at a similar rate to the analogous system derived from phenyl radicals and 1,1-diphenylethene, on the basis of the radical-ionic balance in this reaction (Table 3(b)).

The decomposition of NNA in a benzene solution of dibenzofulvene gave a low yield of benz(e)acephenanthrylene (8 m/100 m NNA), a product assumed to be derived from Diels-Alder addition of benzyne to the dibenzofulvene, followed by a hydrogen shift and oxidation, such additions of arynes to styryl systems are not uncommon.[94]

This confirmed that diversion of the benzyne intermediate into Diels-Alder addition to the promoter would not be a significant competitor with the addition of benzyne to furan. Landells[29] has shown that NNA derived benzyne similarly adds to 1, 1-diphenylethene to give a 9% yield of Diels-Alder adduct in benzene solution.

Dibenzofulvene was therefore as efficient a benzyne promoter as 1, 1-diphenylethene but its use has practical disadvantages in that it is difficult to synthesise in high yield and purity due to its instability at room temperature in air.[161]

The π system of 1, 1-(4, 4'-biphenylyl)ethene, while lacking the rigid coplanarity of dibenzofulvene, has a greater potential for delocalisation of the unpaired electron in the phenyl radical adduct (Scheme 22); as with 1, 1-diphenylethene simultaneous coplanarity of the two groups on the 1-position of the ethene is sterically unfavourable.

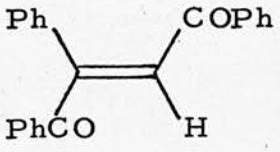


Scheme 22

The low solubility of the alkene meant that standard conditions of 1 mole of alkene per mole of NNA could not be achieved, but data available from Murray's work in which he had used 0. 1 moles of 1, 1-diphenylethene per mole of NNA allowed a valid comparison to be made (Table 3(b)). Again there was no significant improvement in the yield of benzyne derived product over that observed with diphenylethene and since the potential for increased delocalisation is present it can be reasonably assumed that the rate of oxidation of the intermediate radical plays a crucial role in the effectiveness of the promoter.

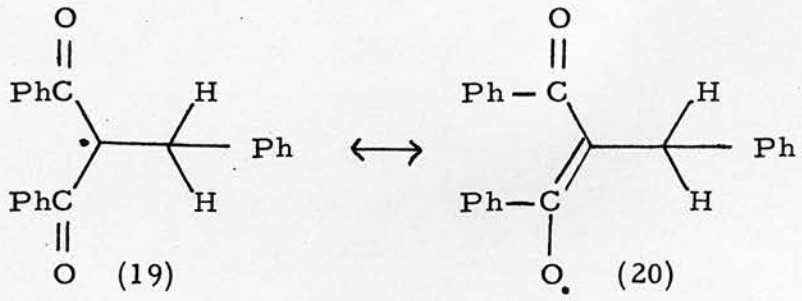
The effect of 1, 1-dibenzoylethene was examined because of the relatively high efficiency of 1, 2, 4-triphenylbut-2-ene-1, 4-dione (21) as a promoter in that its use gave a high yield of 1, 4-dihydronaphthalen-

1,4-endoxide (43 m/100 m NNA) in the standard benzene-furan system.



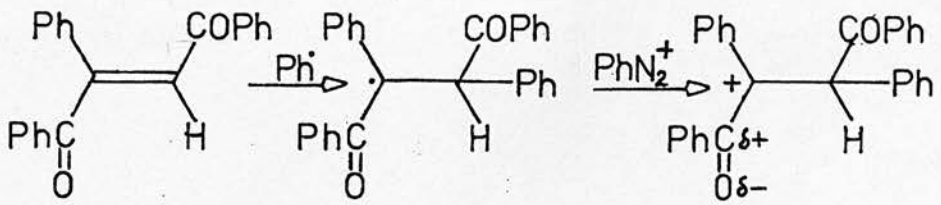
(21)

No benzyne promoting activity, as measured by the formation of a benzyne-furan adduct, was shown by 1,1-dibenzoylethene however; this was presumably due to it being a poor radical trap as a consequence of the two electron withdrawing benzoyl groups depleting the electron density of the π system of the ethylinic double bond; furthermore the inability of the phenyl radical-alkene adduct (19) to adequately delocalise the unpaired electron would decrease the thermodynamic impetus for radical trapping since conjugation of the radical centre with the phenyl rings is impossible and conjugation with the carbonyl function (20) does not confer great stabilisation.



Support for this comes from the fact that the rate constant for radical induced polymerisation propagation is fifteen times greater for methyl acrylate than for styrene,[6(a)] indicating the low radical delocalisation contribution from the carbonyl function on the former.

1,2,4-Triphenylbut-2-ene-1,4-dione could have had a mode of action more akin to that of tetracyclone than the hydrocarbon alkenes so far examined, in that while the formation of an adduct with a phenyl radical would be favoured by the potential for high delocalisation of the unpaired electron on a phenyl system oxidation of the adduct would be made less favourable by the electron withdrawing carbonyl function in conjugation with the radical or cation centre.



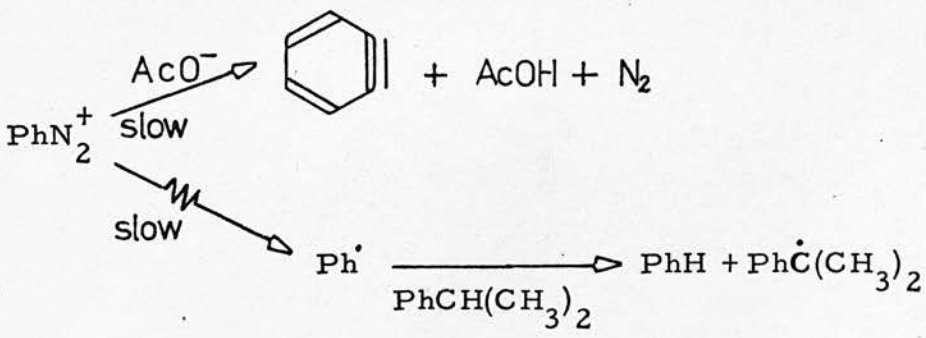
(21)

Such inhibition of oxidation would retard the radical chain process which is competing with the ionic benzyne formation.

From these results it may be concluded that although a promoter must be able to efficiently trap phenyl radicals to give an intermediate of relatively low radical activity by delocalisation of the unpaired electron into a large π system, the resistance of this delocalised system to oxidation, probably by the benzenediazonium cation, will ultimately determine the overall efficiency in promoting benzyne formation. It has been shown that the presence of one phenyl group in conjugation with the double bond in the promoter is necessary while the presence of electron withdrawing functions which are in conjugation with the adduct radical increase the resistance of the radical to oxidation. These observations strongly suggest that the major mode of action of olefinic benzyne promoters is efficient trapping of chain carrying phenyl radicals into a relatively slow redox chain reaction (Scheme 20) and not efficient trapping followed by disproportionation of the adduct radicals (Scheme 19).

The Decomposition of NNA in Cumene and Furan

Cumene has a benzylic hydrogen which may be easily abstracted by phenyl and benzoyloxy radicals[186] and it was hoped that abstraction of the benzylic hydrogen by phenyl radical chain carriers would terminate free radical chain reactions and promote ionic benzyne formation. This would have the obvious advantage of the solvent also functioning as the aryne promoter and thus reducing the complexity of the system (Scheme 23).



no fast chain reaction

Scheme 23

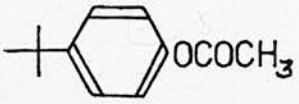
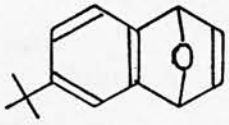
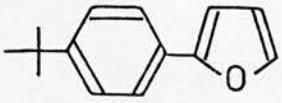
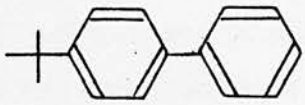
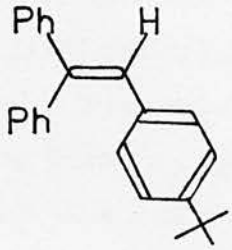
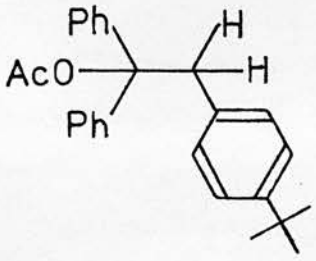
The report[186] of high yields of bicumyl when NNA was decomposed in cumene suggested that such an abstraction process is a significant pathway.

The yield of benzyne derived 1,4-dihydronaphthalen-1,4-endoxide (14.5 m/100 m NNA) observed when NNA was decomposed in furan and cumene at 60° was twice that observed by Murray for NNA decomposition in furan and benzene (7 m/100 m NNA) although the yield of phenyl acetate was approximately the same (2.2 m/100 m NNA); correspondingly the yield of 2-phenylfuran was 24 m/100 m NNA, half that observed in the furan and benzene system. These results indicate that cumene promotes the formation of benzyne in the presence of furan, but not sufficiently to make this a useful medium in which to carry out such reactions.

The observation of benzene in the product mixture as 23 m/100 m NNA confirmed that benzylic hydrogen was being abstracted by phenyl radicals in significant amounts, and the relatively low degree of benzyne formation as measured by the yield of furan adduct was therefore surprising. It is possible that oxidation by the benzenediazonium cation of the cumyl radical to the cumyl cation may be taking place relatively quickly, allowing the formation of phenyl radicals which hydrogen abstract from cumene to give cumyl radicals and thus continue the chain reaction and remove benzenediazonium cations from the system.

Table 4(b)

The Decomposition of N-Nitroso-4-t-butylacetanilide

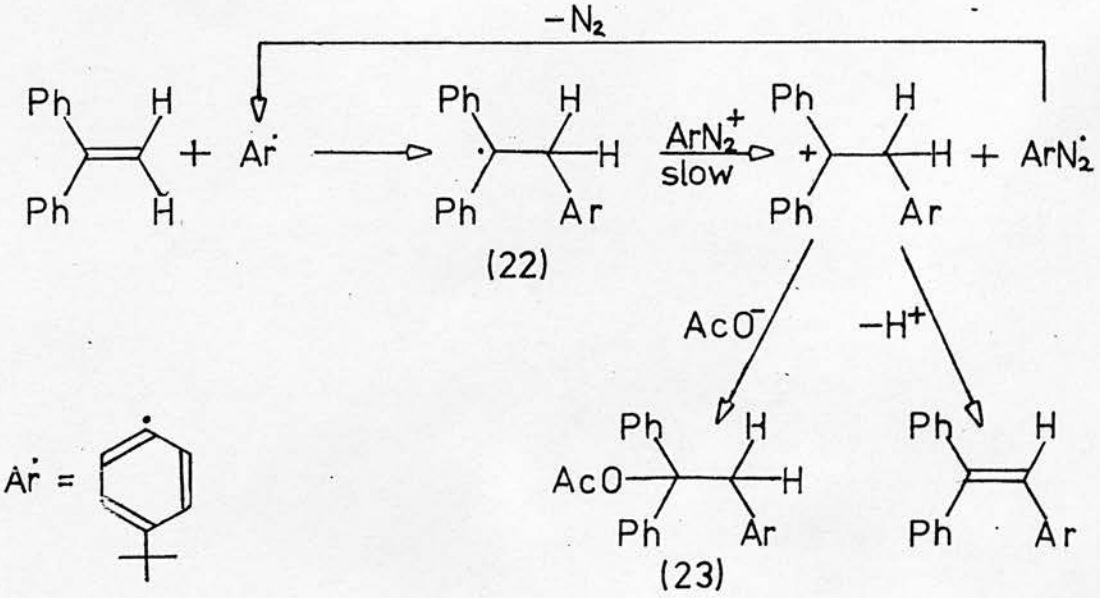
Reaction medium	Benzene + Furan	Benzene + Furan + 1, 1-Diphenylethene
Product (%)		
	1.5	13
	3	31
	58	10
	13	2
		8
		6
Accountance	75.5	70

The Decomposition of Acetylarylnitrosamines in Benzene Furan and 1, 1-Diphenylethene

N-Nitroso-4-t-butylacetanilide

The use of 1, 1-diphenylethene as an aryne promoter in the decomposition of N-nitroso-4-t-butylacetanilide was successful in that the yields of 4-t-butylphenylacetate and 6-t-butyl-1, 4-dihydronaphthalen-1, 4-endoxide, products of ionic reaction, showed a tenfold increase over the reaction in the absence of promoter while the yields of 4-t-butylphenyl radical derived 4-t-butylbiphenyl and 2-(4-t-butylphenyl)-furan showed a 6-fold diminution (Table 4(b)). The identification of 1, 1-diphenyl-2-(4-t-butylphenyl)ethene was consistent with the role of 1, 1-diphenylethene acting as an aryl radical trap and retarding radical chain processes.

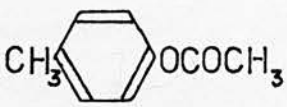
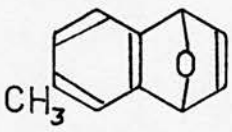
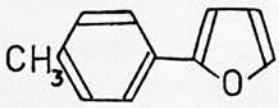
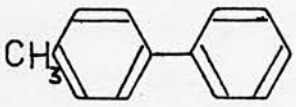
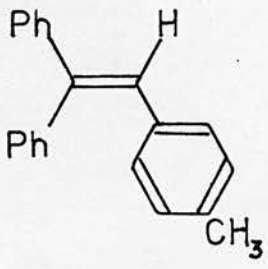
Most mechanistically significant however was the isolation and identification of 1, 1-diphenyl-2-(4-t-butylphenyl)ethyl acetate (6 m/100 m nitrosamide) which provided additional evidence for the hypothesis that the promoter was itself taking part in a chain process which incorporated the aryldiazonium cation as an oxidant of the promoter-arylradical adduct (22) which then may have eliminated a proton or added to acetate (Scheme 24).



Scheme 24

Table 5(b)

The Decomposition of N-Nitroso-4-methylacetanilide

Reaction medium	Benzene + Furan	Benzene + Furan + 1, 1-Diphenylethene
Product (%)		
	undetected	0.4
	undetected	undetected
	33	6
	11	1.4
		15
Accountance	44	22.8[†]

[†] large amount of unidentified polymeric product.

Although Murray did not identify an analogous acetate product in the decomposition of NNA in benzene, furan and 1, 1-diphenylethene this may be due to the fact that the compound cannot be detected by gas liquid chromatography under the conditions normally used, since (23) was not detected by g. c.

The lower yields of endoxide and arylacetate products observed from N-nitroso-4-t-butylacetanilide compared with those obtained from unsubstituted NNA (50 m endoxide and 25 m acetate/100 m NNA) could be due to a lowering of the acidity of the protons adjacent to the diazonium function by the inductive electron donating effect of the t-butyl group making the proton abstraction by acetate less energetically favourable.

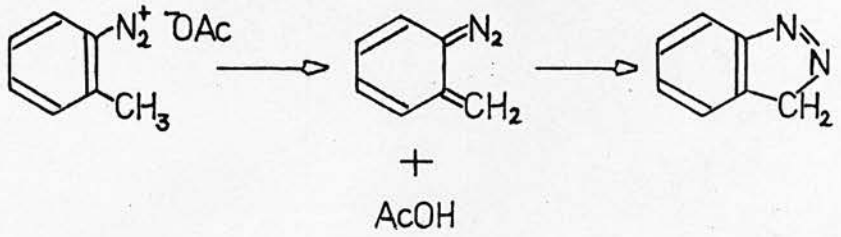
N-Nitroso-4-methylacetanilide

The experimental results for this compound (Table 5(b)) show that while the addition of 1, 1-diphenylethene as an aryne promoter and radical trap caused a sizeable diminution in yields of the free radical derived 4-methylbiphenyl and 2-(4-methylphenyl)furan the expected concomitant increase in the yields of products derived from ionic mechanisms was absent. In this experiment 4-methylphenylacetate was only present as 0.4 m/100 m nitrosamide while g. c. -m. s. failed to identify any component in the mixture which could be attributed to 6-methyl-1, 4-dihydronaphthalen-1, 4-endoxide. When the reaction was repeated on a preparative scale only an amorphous solid (1. 1 g from 2. 6 g nitrosamide) could be separated by trituration and n. m. r. and i. r. spectroscopy indicated this to be polymeric.

The estimated yield of 1, 1-diphenyl-2-(4-methylphenyl)ethene (15 m/100 m nitrosamide) did not indicate that the low accountancy was to any abnormal degree associated with the radical chain arylation of 1, 1-diphenylethene.

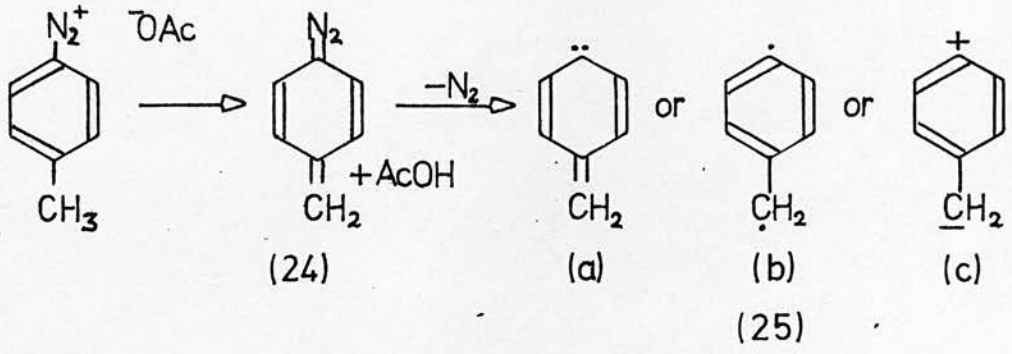
A clue to the absence of aryne derived products in the presence of aryne promoter can perhaps be obtained from Huisgen's[187] observation that N-nitroso-2-methylacetanilide, when allowed to decompose in most

organic solvents gave high yields of indazole (Scheme 25).



Scheme 25

The presence of promoter during the decomposition of N-nitroso-4-methylacetanilide would be expected to allow reactions of of the type shown in Scheme 25 to predominate; in this case however the intermediate (24) would not be capable of intramolecular cyclisation (Scheme 26).



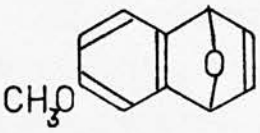
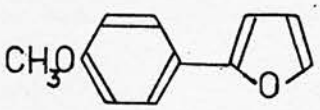
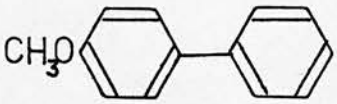
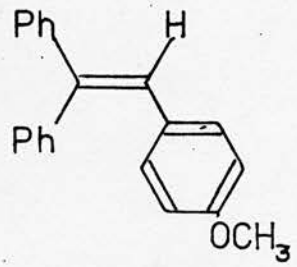
Scheme 26

This diazide intermediate (24) could subsequently decompose thermally with loss of nitrogen to a reactive intermediate of the type (25a)(b) or (c) which would subsequently react with benzene and 1, 1-diphenylethene; if the reactive intermediate had high diradical or carbene character it might undergo polymerisation reactions with 1, 1-diphenylethene.

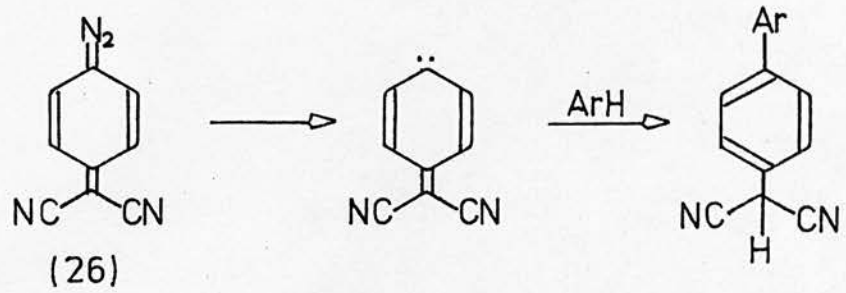
Support for this proposed mechanism comes from Hartzler's observation that the photolysis or thermolysis of 3-diazo-6-dicyanomethylene-1, 4-cyclohexadiene (26) in aromatic solvents gives low yields of biaryls

Table 6(b)

The Decomposition of N-Nitroso-4-methoxyacetanilide

Reaction medium	Benzene + Furan	Benzene + Furan 1, 1-Diphenylethene
Product (%)		
	undetected	0.6
	undetected	1.7
	50	12
	12	4
		21
Accountance	62	39.3

and considerable amounts of unidentified noncrystalline material[188] (Scheme 27).



Scheme 27

Although no bibenzyl was detected by Hartzler when ArH = toluene, it was not possible to state convincingly whether the structure of the intermediate had been of the type (25a), (25b) or (25c) (Scheme 26).

The failure to detect the formation of 4-methylbenzyne from N-nitroso-4-methylacetanilide could therefore be due to presence of a lower energy ionic pathway in the abstraction of a methyl proton by acetate from the 4-methylbenzenediazonium cation making the abstraction of a proton adjacent the diazonium function energetically unfavourable.

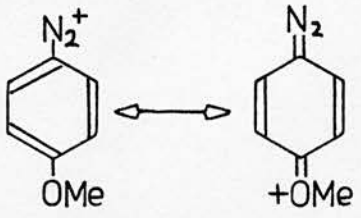
N-Nitroso-4-methoxyacetanilide

In the benzene-furan system ionic reaction as measured by endoxide and aryl acetate products is negligible (see Table 6(b)) while even in the presence of 1, 1-diphenylethene promoter the yields of these ionic-derived products are very low suggesting that there is some strong impediment to ionic reaction.

The free radical reactions give rise to high yields of 4-methoxybiphenyl and 2-(4-methoxyphenyl)furan in the absence of promoter and when it is present show a marked diminution in yield indicating that 1, 1-diphenylethene has been acting to suppress the radical chain processes but despite this ionic reaction has not significantly increased. The relatively high yield of 1, 1-diphenyl-2-(4-methoxyphenyl)ethene

(21%) confirms that the free radical arylation of 1, 1-diphenylethene had been taking place and therefore that the promoter had been acting in its primary role as a radical trap; the blank reaction in which authentic 6-methoxy-1, 4-dihydronaphthalen-1, 4-endoxide had been added to the reaction medium confirmed that any endoxide product formed would be stable under the reaction conditions.

It can only be suggested that despite retardation of the radical chain process by 1, 1-diphenylethene, ionic reaction to give acetate and endoxide products was very slow relative to the radical processes. A possible reason for this would be stabilisation of the diazonium function by charge delocalisation from the oxygen in the methoxy group giving the carbon-nitrogen bond some additional double bond character (27).



(27)

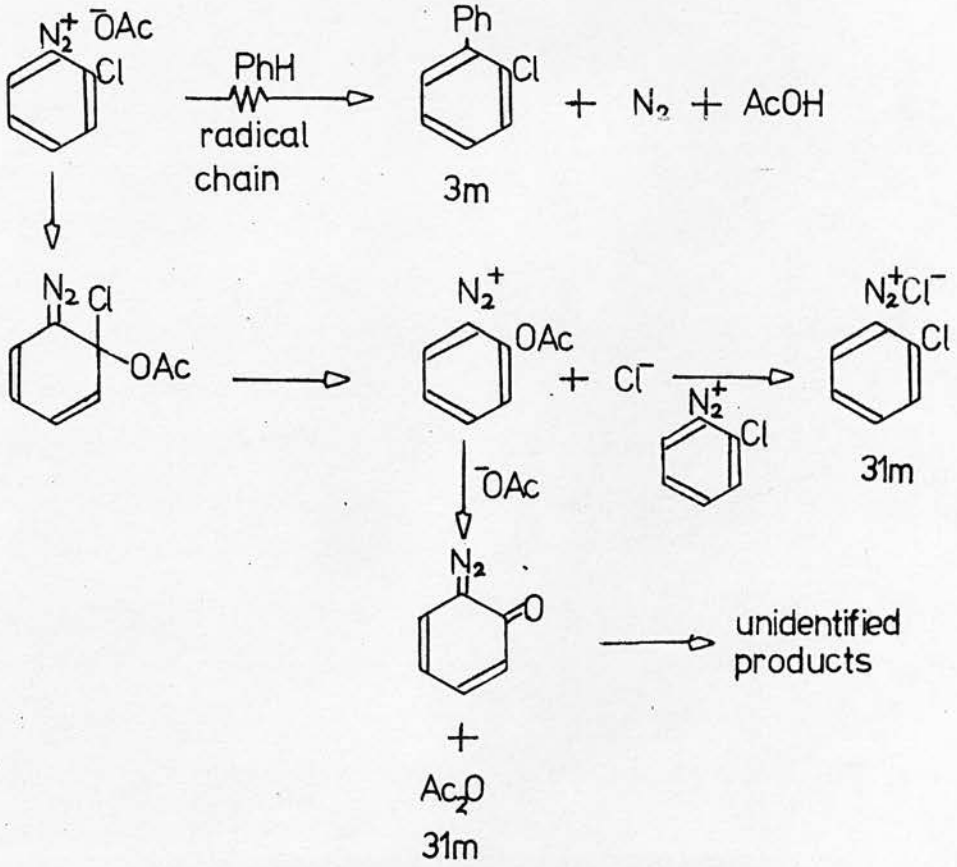
This would raise the activation energy for the elimination of an ortho proton and nitrogen to yield the desired aryne intermediate; similarly the activation energy for the displacement of nitrogen by acetate would be increased. However once cation (27) had been reduced to the 4-methoxyphenyldiazo radical loss of nitrogen would be fast.

It can therefore be concluded that while the use of 1, 1-diphenylethene as a promoter gave rise to useful quantities of 6-t-butyl-1, 4-dihydronaphthalen-1, 4-endoxide from N-nitroso-4-t-butylacetanilide in furan and benzene at 60° the decompositions of N-nitroso-4-methylacetanilide and N-nitroso-4-methoxyacetanilide under identical conditions showed no promise as synthetic routes to the corresponding endoxide products.

The Decomposition of N-Nitrosochloroacetanilides in Benzene and 1,1-Diphenylethene

N-Nitroso-2-chloroacetanilide

When N-nitroso-2-chloroacetanilide was allowed to decompose in benzene and 1,1-diphenylethene at 50° the formation of 2-chlorobiphenyl, acetic anhydride and insoluble 2-chlorobenzenediazonium chloride represented the major identified reactions, for which mechanisms are proposed (Scheme 28).



Scheme 28

Acetic anhydride from this reaction and those discussed subsequently was estimated from the yield of acetamide obtained by reaction of aniline or 4-methylaniline with the reaction mixture upon completion of decomposition of the acetylarylnitrosamine.

The 2-chlorobiphenyl presumably arose via the normal free radical arylation mechanism while the formation of 2-chlorobenzenediazonium chloride and acetic anhydride are best rationalised in terms of the mechanisms shown, the crucial step being ionic displacement of chloride by acetate from the 2-chlorobenzenediazonium cation. The failure to account for products associated with the aromatic nucleus of the postulated 2-acetoxybenzenediazonium cation or the 1, 2-benzoquinone-2-diazide is disappointing, although the decomposition of authentic N-nitroso-2-acetoxyacetanilide under similar conditions only yielded 3 moles of product associated with the aromatic nucleus per 100 moles of nitrosamide, and a high yield of acetic anhydride (96 m/100 m nitrosamide).

The apparent exclusive formation of 2-chlorobenzenediazonium chloride and absence of any 2-acetoxybenzenediazonium chloride could have resulted from attack on the latter by acetate to yield acetic anhydride, 1, 2-benzoquinone-2-diazide and chloride ion which subsequently reacted with the 2-chlorobenzenediazonium cation; such a mechanism would be acceptable where there existed a high concentration of 2-chlorobenzenediazonium cations in solution, which would be expected in the presence of 1, 1-diphenylethene.

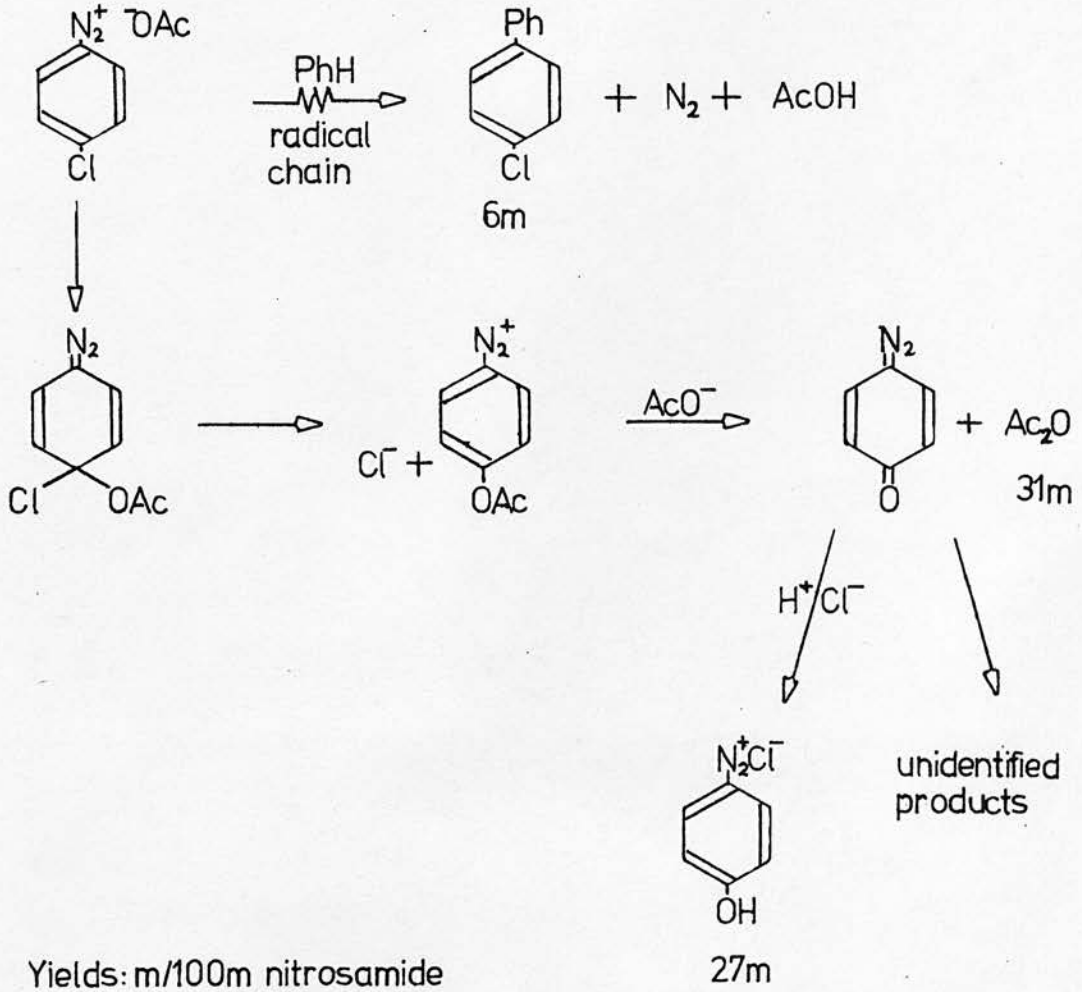
The free-radical trapping effect of 1, 1-diphenylethene was illustrated by the identification of 1, 1-diphenyl-2-(2-chlorophenyl)ethene as 5.5 m/100 m nitrosamide, suggesting that the promoter had been acting to retard the normal radical chain mechanism which in this case also gave rise to 3 moles 2-chlorobiphenyl per 100 moles of nitrosamide.

In the absence of 1, 1-diphenylethene promoter the major product of the decomposition of N-nitroso-2-chloroacetanilide in benzene at 50° was the expected free radical derived 2-chlorobiphenyl (69 m/100 m nitrosamide). There was however a small amount of acetic anhydride (2 m/100 m nitrosamide) and precipitated 2-hydroxybenzenediazonium chloride (0.9 m/100 m nitrosamide) which may have resulted from substitution of chloride by acetate giving rise to the 1, 2-benzoquinone-2-diazide which was protonated to form the 2-hydroxybenzenediazonium cation; this was then precipitated as the chloride. This would be in

keeping with the fact that while the ionic displacement processes outlined result in the formation of acetate ion, the free radical processes result in the formation of acetic acid.

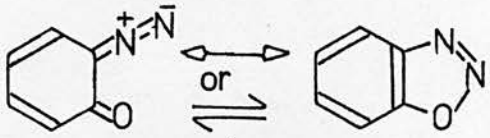
N-Nitroso-4-chloroacetanilide

When N-nitroso-4-chloroacetanilide was allowed to decompose in benzene and 1, 1-diphenyl ethene at 50° the result was similar but not analogous to that observed with the 2-isomer. In the 4-chloro case the main products were 4-chlorobiphenyl, acetic anhydride and a precipitate of 4-hydroxylbenzenediazonium chloride; the proposed mechanism for the formation of these principally involves ionic processes (Scheme 29).



Scheme 29

The formation of 4-hydroxybenzenediazonium chloride as the product of ionic exchange may be due to the high tendency of the postulated 1,4-benzoquinone-4-diazide intermediate to re-aromatise by protonation of the carbonyl oxygen to yield a 4-hydroxybenzenediazonium cation; that such a protonation mechanism was not dominant in the 1,2-benzoquinone-2-diazide case may have been because of the potential for internal rearomatisation by a tautomerism or resonance process (Scheme 30).



Scheme 30

One limiting factor on the protonation of the 1,4-benzoquinone-4-diazide will have been the degree of free radical reaction involving oxidation and elimination of a proton; the arylation of benzene and 1,1-diphenylethene are two such identified reactions, the latter again indicating that radical trapping, and inhibition of fast chain processes was effective; the estimated yield of 1,1-diphenyl-2-(4-chlorophenyl)-ethene was 9 m/100 m nitrosamide.

Other evidence for the intermediacy of the 4-acetoxybenzenediazonium ion was the identification of acetic anhydride as 31 m/100 m nitrosamide; the decomposition of N-nitroso-4-acetoxyacetanilide under similar conditions gives rise to high yields of acetic anhydride and low yields of products derived from the aromatic nucleus.

The decomposition of N-nitroso-4-chloroacetanilide in benzene at 50° gave rise to the expected high yield of free radical derived 4-chlorobiphenyl (68 m/100 m nitrosamide). Small amounts of acetic anhydride (6 m/100 m nitrosamide) and 4-hydroxybenzenediazonium chloride (3.7 m/100 m nitrosamide) were observed suggesting that in the absence of the radical chain inhibition free radical reactions predominate, but are not exclusive.

N-Nitroso-3-chloroacetanilide

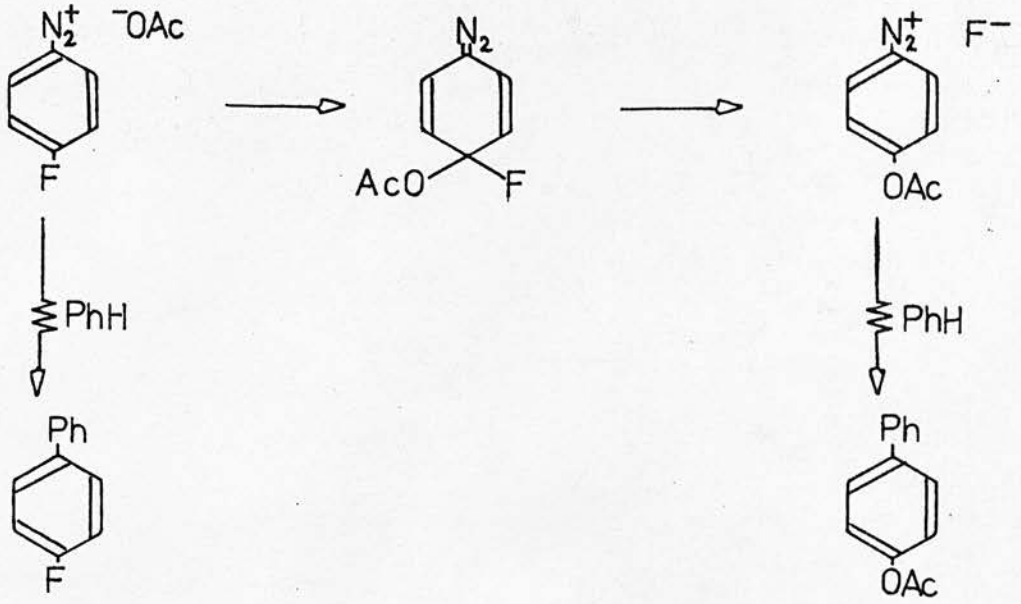
Because N-nitroso-3-chloroacetanilide is an oil at room temperature the strictly anhydrous conditions used for the 2- and 4-isomers could not be replicated (see experimental section) but it is probable that the contaminant acetic anhydride present would remove most moisture. When N-nitroso-3-chloroacetanilide in benzene and 1, 1-diphenylethene was allowed to decompose at 50° only two products were identified as being present and both are compounds assumed to be derived from free-radical chain reactions; these were 3-chlorobiphenyl (14 m/100 m nitrosamide) and 1, 1-diphenyl-2-(3-chlorophenyl)ethene (30 m/100 m nitrosamide). The high yields of both of these compared with those observed from the 2- and 4-isomers suggest a far higher degree of free radical reaction.

In benzene at 50° N-nitroso-3-chloroacetanilide decomposed to give a high yield of the expected 3-chlorobiphenyl (63 m/100 m nitrosamide) and no evidence for ionic exchange was apparent.

General Remarks on the Thermal Decomposition of N-Nitrosochloroacetanilides.

The nucleophilic displacement of functional groups from the aryl nuclei of acetylarylnitrosamines has only been reported once previously, when Suschitzky[117] observed that N-nitroso-2- and 4-fluoroacetanilides decomposed in benzene to give both the corresponding fluorobiphenyls and the corresponding acetoxybiphenyls, and for which he proposed an ionic mechanism (Scheme 31).

He also observed that such displacement did not take place in the 3-fluoro case nor in the cases of other N-nitrosohaloacetanilides; he concluded that the reason for the former observation was the inability of the diazonium function to sufficiently activate the 3-position while in the latter cases the halo substituents were not rendered sufficiently labile by the diazonium function to undergo displacement.



Scheme 31

The work presented here has shown even in benzene N-nitroso-2- and 4-chloroacetanilides will undergo a small degree of nucleophilic displacement of the halogen and when 1, 1-diphenylethene is also present nucleophilic displacement of halogen becomes the major reaction pathway.

Suschitzky's failure to observe nucleophilic displacement in the decomposition of N-nitroso-2- and 4-chloroacetanilides in benzene may have been due to his primary criterion for exchange being the formation of acetoxybiphenyls, while it has been shown here that even where a high concentration of acetoxybenzenediazonium cation is expected the resulting yields of acetoxybiphenyls are low. The high degree of exchange observed in the 2- and 4-chloro cases with 1, 1-diphenylethene present suggest that the major impediment to ionic displacement on the aromatic nucleus in the absence of promoter is the fast removal of diazonium cations from solution by incorporation into radical chain processes, and when such processes are retarded the thermodynamically favourable nucleophilic displacement reactions take place.

The failure to observe any ionic exchange reactions on the

aromatic nucleus of the 3-chlorobenzenediazonium cation is not surprising and in keeping with the observed inability of the diazonium function to activate the 3-position and to adequately stabilise any resulting intermediate.

These results are all in keeping with the proposed role of 1, 1-diphenylethene as a radical chain reaction inhibitor and ionic reaction promoter.

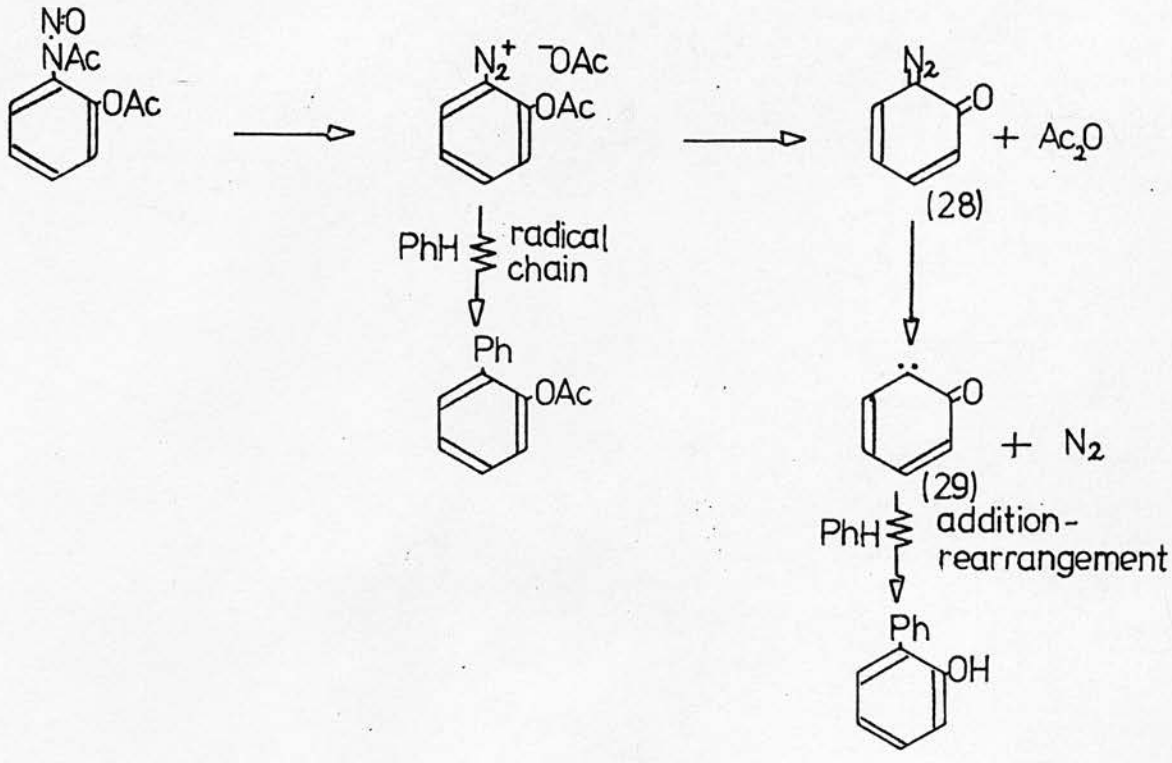
The Decompositions of N-Nitrosoacetoxyacetanilides and Related Reactions.

The proposed intermediacy of 2- and 4-acetoxybenzenediazonium cations in the decomposition of 2- and 4-chlorobenzenediazonium acetates suggested that a study of directly generated acetoxybenzenediazonium cations would be of interest, especially with regard to their role as benzoquinone diazide precursors.

N-Nitroso-2-acetoxyacetanilide

When N-nitroso-2-acetoxyacetanilide was allowed to decompose in boiling benzene the yield of 2-acetoxybiphenyl (13 m/100 m nitrosamide) was lower than expected; the presence of 2-hydroxybiphenyl (1.5 m/100 m nitrosamide) and acetic anhydride (27 m/100 m nitrosamide) furnished further evidence that mechanisms other than solely free radical arylation were operative. It was considered unlikely that the 2-hydroxybiphenyl had arisen from impure starting material since i.r. spectroscopy had not indicated the presence of any hydroxy function in the N-nitroso-2-acetoxyacetanilide.

The mechanism which best fits these results is one of a free radical chain reaction giving rise to the 2-acetoxybiphenyl and competing attack of the acetate ion on the acetoxy group of the 2-acetoxybenzenediazonium cation giving acetic anhydride and 1, 2-benzoquinone-2-diazide (28); loss of nitrogen from the latter would yield 1-carbeno-2-oxocyclohexa-3, 5-diene (29) which would attack benzene and rearrange to form 2-hydroxybiphenyl (Scheme 32).

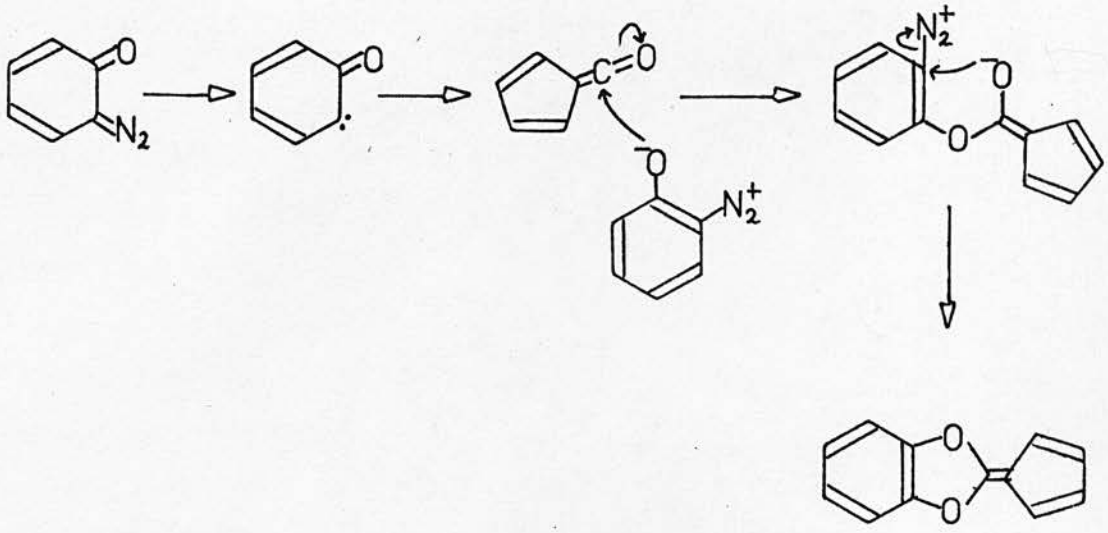


Scheme 32

The decomposition of the diazide (29) in benzene has been reported[174] to give 2-hydroxybiphenyl (11%) and 1,4-dioxa-2,3-benzofulvalene (16%); the latter was not observed in this system. Further support for this scheme came from the decomposition of N-nitroso-2-acetoxyacetanilide in benzene and 1,1-diphenylethene, a system in which the homolytic-heterolytic mechanism balance would be expected to favour heterolytic reaction. In this system the yield of free radical derived 2-acetoxybiphenyl fell to 1.7 m/100 m nitrosamide while the yield of acetic anhydride rose to 96 m/100 m nitrosamide and the yield of hydroxybiphenyl remained approximately constant; the last observation could be explained by higher yields of carbene (29) but subsequent trapping by 1,1-diphenylethene.

The absence of the carbene derived 1,4-dioxa-2,3-benzofulvalene (30) expected to be formed from the diazide (Scheme 33) was surprising.

It is possible that in the absence of 1,1-diphenylethene the acetic acid derived from free radical reactions was suppressing the above reaction while the reason for the failure to observe the fulvalene (30)



(30)

Scheme 33

in benzene and 1, 1-diphenylethene is less clear.

The intermediacy of 1, 2-benzoquinone-2-diazide and 1-carbeno-2-oxocyclohexa-3, 5-diene derived from N-nitroso-2-acetoxyacetanilide was convincingly illustrated by the decomposition of the latter in either boiling p-xylene or boiling cumene when yields of 1, 4-dioxa-2, 3-benzofulvalene of up to 11 m/100 m nitrosamide were obtained (Scheme 33); the presence of 1, 1-diphenylethene (1 mol/mol nitrosamide) in p-xylene did not affect the yield of fulvalene product, suggesting that radical chain reactions are not significant competitors with the carbene forming process in this system.

In conclusion N-nitroso-2-acetoxyacetanilide has been shown to be an efficient precursor for the generation of 1-carbeno-2-oxocyclohexa-3, 5-diene, formed via the intermediacy of 1, 2-benzoquinone-2-diazide, in p-xylene; the failure to observe significant amounts of products derived from this carbene in benzene and 1, 1-diphenylethene suggest that polymerisations may have constituted a major mode of reaction however the high yields of acetic anhydride observed were in keeping with the formation of the carbene precursor, 1, 2-benzoquinone-2-diazide.

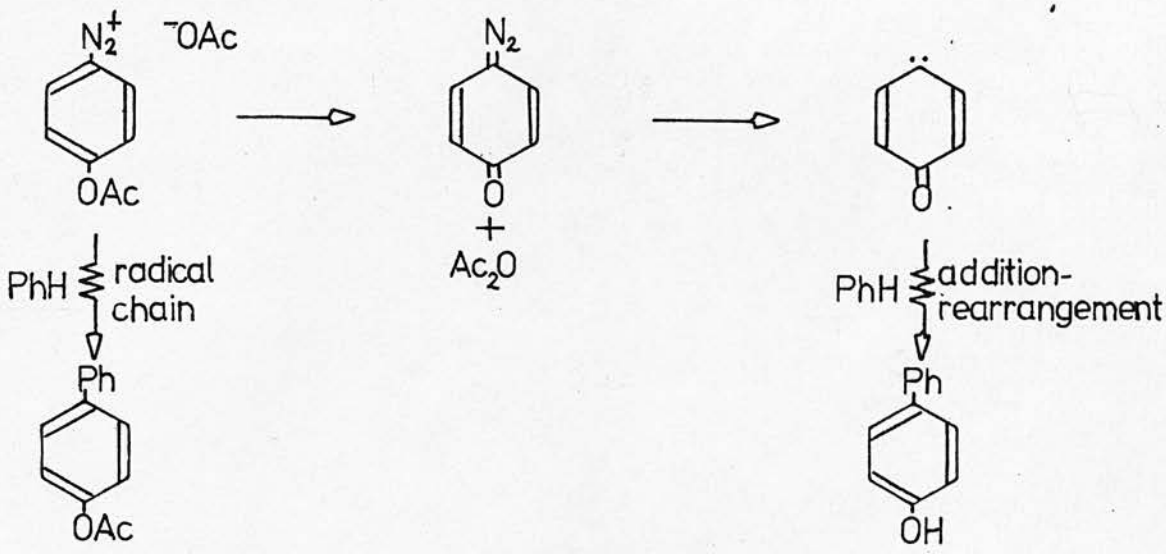
N-Nitroso-4-acetoxyacetanilide

The decomposition of N-nitroso-4-acetoxyacetanilide in benzene at 50° was broadly characteristic of the decomposition of an acetylarylnitrosamine in benzene in that the major product was the free radical derived biaryl, 4-acetoxybiphenyl (50 m/100 m nitrosamide) while evidence for an ionic process analogous to that observed in the decomposition of the 2-acetoxy isomer was present in the form of 4-hydroxybiphenyl (8 m/100 m nitrosamide) and acetic anhydride (35 m/100 m nitrosamide) the latter measured by its reaction with aniline. In further support of this when the reaction was repeated in the presence of 1, 1-diphenylethene the yield of 4-acetoxybiphenyl fell to 2. 5 m/100 m nitrosamide, while the yield of acetic anhydride rose to 82 m/100 m nitrosamide; the yield of 4-hydroxybiphenyl also fell however.

A surprising observation was that after this solution had stood exposed to air overnight a high yield of benzophenone was observed and there was still a slow evolution of gas.

In order to clarify the origin of this anomalous product N-nitroso-4-acetoxyacetanilide was decomposed in boiling benzene and 1, 1-diphenylethene under nitrogen (as previously) until all gas evolution from the reaction mixture had ceased; yields of 4-acetoxy- and 4-hydroxybiphenyl had risen to 12. 5 m and 4 m/100 m nitrosamide respectively and the yield of benzophenone was much lower (8 m/100 m nitrosamide); this yield did not increase upon subsequent exposure to air and heating. The proposed basic mechanism for the decomposition at 80° in benzene and 1, 1-diphenylethene is outlined (Scheme 34).

The benzophenone observed in high yield from the reaction at 50° was probably a consequence of relatively fast rearrangement of the 4-acetoxybenzenediazonium acetate to acetic anhydride and 1, 4-benzoquinone-4-diazide; the latter had not decomposed completely when reaction was assumed to be complete (by the criterion of gas evolution apparently having ceased) and in the presence of atmospheric oxygen acted to oxidise 1, 1-diphenylethene to benzophenone. When the reaction



Scheme 34

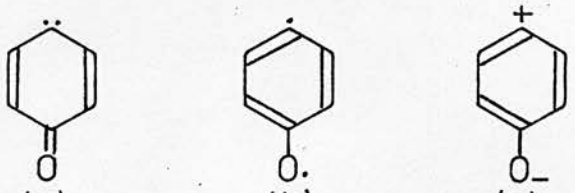
was repeated at 80° and all nitrogen evolution had definitely ceased before exposure to atmospheric oxygen the yield of benzophenone was much lower and did not subsequently increase; in this case benzophenone probably arose from air entering the system when the nitrosamide was added.

The formation of 4-acetoxybiphenyl was assumed to have taken place by the normal free radical chain process while the high yield of acetic anhydride (measured by reaction with aniline) most probably arose by attack of acetate on the acetoxy group on the 4-acetoxybenzenediazonium cation to form 1,4-benzoquinone-4-diazide, which subsequently lost nitrogen to form 1-carbeno-4-oxocyclohexa-2,5-diene; this then reacted with benzene and after rearrangement yielded 4-hydroxybiphenyl. In support for this mechanism the decomposition of 1,4-benzoquinone-4-diazide in benzene and 1,1-diphenylethene yielded 4-hydroxybiphenyl (14 m/100 m diazide) and benzophenone (4 m/100 m diazide); no other products could be identified from the black tarry reaction mixture.

Attempts to isolate further products from the decomposition of

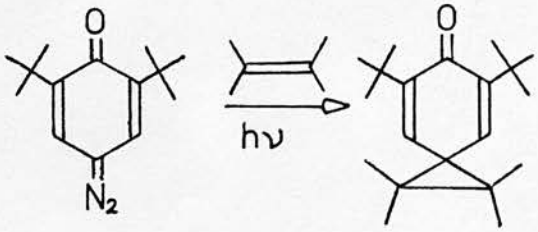
N-nitroso-4-acetoxyacetanilide in benzene and 1, 1-diphenylethene were unsuccessful but it is difficult to predict what such products might have been.

Although it was proposed that the reactive intermediate generated by the loss of nitrogen from 1, 4-benzoquinone-4-diazide would be 1-carbeno-4-oxocyclohexa-2, 5-diene (31a) the exact nature of the intermediate is somewhat controversial; the three forms of the intermediate normally suggested are the carbene (31a) the diradical (31b) and the dipolar species (31c).



(31)

While Dewar[189] obtained mainly polymeric products from the thermolysis of 2, 6-dibromo-1, 4-benzoquinone-4-diazide in high concentration in chlorobenzene at 70° and above, and suggested a 1, 5-diradical as the most probable intermediate, Stille[190] obtained co-polymer from the decomposition of 1, 4-benzoquinone-4-diazide in tetrahydrofuran and suggested that the dipolar species (31c), stabilised by the lone pair on the oxygen of tetrahydrofuran was the intermediate. In contradiction to both of these Wang[191] decomposed 1, 4-benzoquinone-4-diazide, at low concentration, in boiling benzene and isolated 4-hydroxybiphenyl in quantitative yield and suggested a carbene intermediate. Photolysis of 2, 6-di-t-butyl-1, 4-benzoquinone-4-diazide was used by Koser and Pirkle[192] to synthesise bicyclic spiro compounds, and thus provided good evidence for a carbene intermediate (Scheme 35).



Scheme 35

In the absence of t-butyl groups however such spiro[2, 5]octa-4, 7-dien-6-ones are extremely sensitive to acid hydrolysis.[193]

The results obtained for the decomposition of N-nitroso-4-acetoxyacetanilide were therefore consistent with the intermediacy of a species resulting from the loss of nitrogen from 1, 4-benzoquinone-4-diazide; if such a species behaves as a carbene, 1, 5-diradical or zwitterion depending upon solvent conditions then predictions as to the predominant form are unlikely to be fruitful in view of the complexity of the products from the decomposition of N-nitroso-4-acetoxyacetanilide in benzene or benzene and 1, 1-diphenylethene. Similarly it could be suggested that the 1-carbeno-2-oxocyclohexa-3, 5-diene, proposed in the decomposition of 1, 2-benzoquinone-2-diazide, may not be the sole form of the intermediate present.

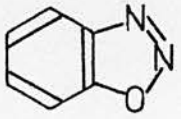
The Decomposition of N-Nitroso-2-chloroacetanilide in p-Xylene

It was hoped that p-xylene would have some retarding effect on free radical chain processes acting in the decomposition of N-nitroso-2-chloroacetanilide in the same way as cumene had been observed to promote the formation of arynes from NNA; in this way some nucleophilic displacement of chloride by acetate would take place and this would give rise to 2-acetoxybenzenediazonium cations or 1, 2-benzoquinone-2-diazide, which might be characterised as 1, 4-dioxa-2, 3-benzofulvalene.

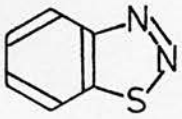
In partial accord with this proposed scheme when N-Nitroso-2-chloroacetanilide was heated in p-xylene a precipitate of 2-chlorobenzenediazonium chloride (15 m/100 m nitrosamide) was observed however addition of the residual solution to boiling p-xylene failed to yield a detectable amount of 1, 4-dioxa-2, 3-benzofulvalene. Although disappointing in the latter respect, the failure to observe any carbene derived product may have been a result of the reaction conditions being unsuitable for the formation of the required concentration of 2-acetoxybenzenediazonium cation or 1, 2-benzoquinone-2-diazide.

The Decomposition of N-Nitroso-2-thioacetoxyacetanilide in Benzene

The proposed intermediacy of 1, 2-benzoquinone-2-diazide in the decomposition of N-nitroso-2-acetoxyacetanilide, and the possibility of the quinone existing as the tautomeric or canonical benzo-1, 2, 3-oxadiazole structure suggested that an analogous route to benzo-1, 2, 3-thiadiazole (32) could be developed since unlike the oxygen compound (31) the sulphur analogue is stable.



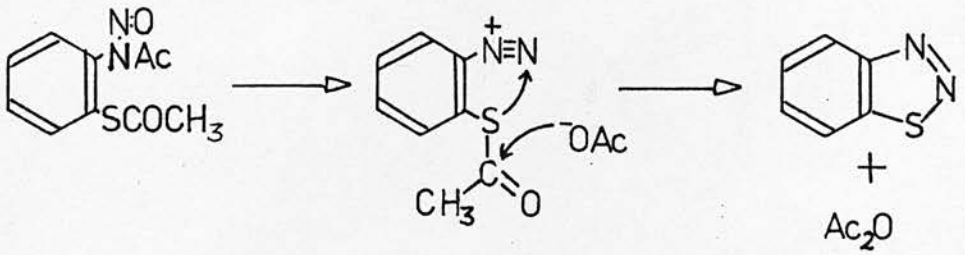
(31)



(32)

These predictions were shown to be correct. When a benzene solution of N-nitroso-2-thioacetoxyacetanilide oil was heated for one hour the yield of benzo-1, 2, 3-thiadiazole was quantitative as measured by g.c. and was isolated pure as 70 m/100 m 2-thioacetoxyacetanilide. The acetic anhydride in the system was not measured since it had been shown that this was a major contaminant of N-nitroso-3-chloroacetanilide oil and it would therefore have been impossible to say whether any acetic anhydride present was derived from the synthesis of N-nitroso-2-thioacetoxyacetanilide or from its subsequent decomposition.

Hydrolysis of the N-nitroso-2-thioacetoxyacetanilide during aqueous work up to give N-nitroso-2-mercaptoacetanilide was considered unlikely in the light of the facts that N-nitroso-2-acetoxyacetanilide can be isolated as a solid using similar techniques, and that phenylthioacetate has been shown by Böhme to be more stable to hydrolysis than phenylacetate under acidic conditions. The proposed mechanism was therefore considered satisfactory (Scheme 36)



Scheme 36

Mechanistically this scheme resembles that invoked for the formation of indazole from N-nitroso-2-methylacetanilide[187] (see p.109).

The Addition of Aryl Radicals to Alkynes and Related Reactions.

The Addition of Aryl Radicals to Dimethylacetylenedicarboxylate.

The reaction of diaroyl peroxides with dimethylacetylenedicarboxylate (DMAD) to give substituted tetramethylnaphthalene-1, 2, 3, 4-tetracarboxylates was shown by Baigrie[144] to be free radical in nature.

Baigrie suggested that the yield of tetramethyl naphthalen-1, 2, 3, 4-tetracarboxylate (50 m/100 m dibenzoyl peroxide) resulted from a 1:1 cis-trans isomerisation of the intermediate styryl and phenylbutadienyl radicals although this proposal had no experimental basis other than the observed yield.

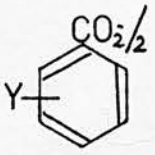
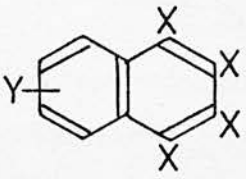
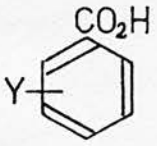
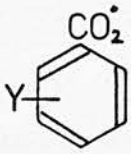
In order to test this hypothesis and to find out if any useful information could be obtained relating to the substantially lower yields of naphthalene derivatives observed from substituted dibenzoyl peroxides it was decided in this investigation to measure the amounts of carbon dioxide evolved and aroic acids formed.

The yields of carbon dioxide evolved would be crucial in determining the efficiency of the decarboxylation process:-

$$ArCO_2^{\bullet} \longrightarrow Ar^{\bullet} + CO_2$$

Table 10

Yields of Products from the Decomposition of Diaroyl Peroxides in Dimethylacetylenedicarboxylate

Peroxide	Products				
				CO_2	 unaccounted
Y=H	50		3	73	125
2-Cl	2.8 (5-Cl)		13	68	119
4-Cl	22 (6-Cl)*		10	57	134
3-Me	19 (5-+6-Me)*		10	66	124
4-Me	16 (6-Me)*		11	62	127

Yields in m/100 m peroxide

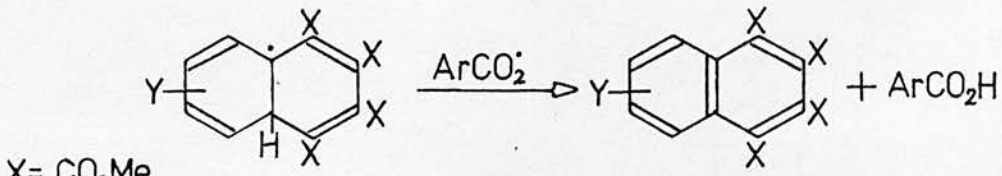
X=CO_2Me

* Baigrie's results[144]

This would allow an estimate of the quantity of aryl radicals available for addition to DMAD; the presence of aroic acids in the reaction mixtures would point to alternative decomposition modes of the diaroyl peroxides and also give some insight into the mechanism of the final oxidation step which had not been previously elucidated.

The results obtained are tabulated facing p. 128; the most significant observation is that any rationalisation of the mechanism based upon 1 mole of dibenzoyl peroxide cleanly decarboxylating in DMAD at 80° to give two moles of phenyl radicals and two moles of carbon dioxide must be discarded. In all of the cases examined the yields of carbon dioxide were between 56 and 72 moles per 100 moles peroxide when complete decarboxylation would have yielded 200 moles of carbon dioxide. If the quantities of aryl radicals generated are equated with the amounts of carbon dioxide evolved then the reaction of phenyl radicals with DMAD can be calculated as being approximately 70% efficient, while the reactions of the 3- and 4-substituted phenyl radicals with DMAD are 25-40% efficient and the reaction of 2-chlorophenyl radicals with DMAD is only 6.5% efficient as measured by naphthalene tetraester products.

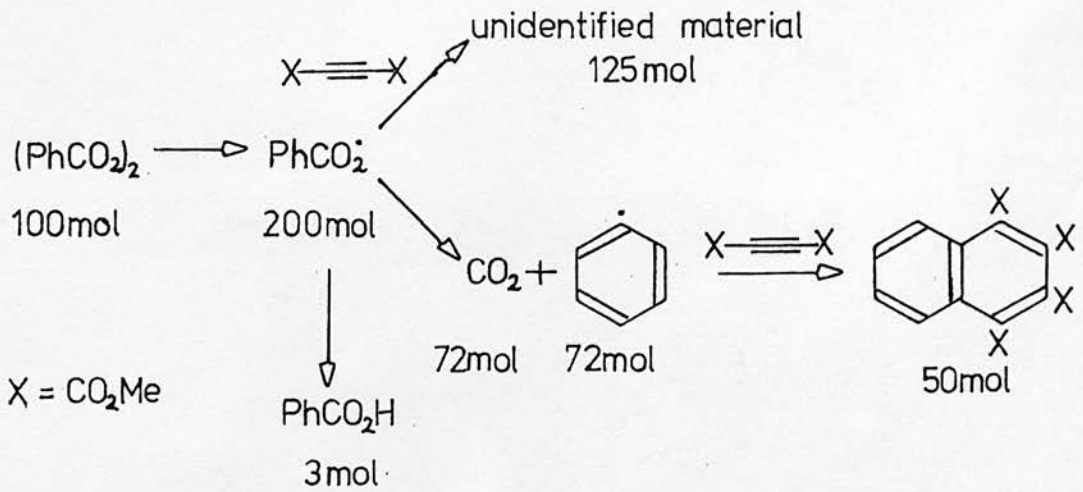
The low yields of aroic acids in all cases indicate that hydrogen abstraction by aroyloxy radicals either from intermediates of the type (33) or from DMAD does not constitute an important mechanistic pathway.



(33)

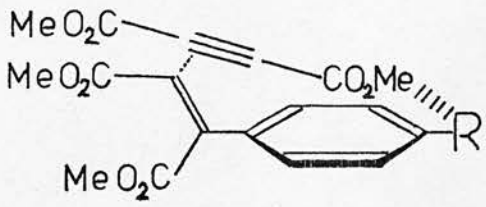
Consequently after allowing for the decarboxylated aroyloxy radicals and for hydrogen abstraction by aroyloxy radicals between 120 and 140 moles of aroyloxy radicals per 100 moles of diaroyl peroxide remain unaccounted for in every case.

The reaction of phenyl radicals with DMAD would appear to result in a preponderance of styryl radicals in the correct configuration for cyclisation and a preponderance of phenylbutadienyl radicals in the correct configuration for cyclisation since 70% of the available phenyl radicals are incorporated in cyclised product. Evidence for this was seen in the decomposition of dibenzoyl peroxide in DMAD where the major product, dimethyl 1, 2-diphenylmaleate, would have been formed via the intermediacy of a styryl radical in the configuration necessary to yield the naphthalene tetraester by reaction with a further molecule of DMAD. Styryl and vinyl radicals have been shown to exist in cis-trans equilibrium and the styryl radicals in this reaction may have been in such an equilibrium. It has been shown by Singer and Kong[195] that approach of a reactant molecule to certain styryl radicals is sterically controlled such that the reactant enters into reaction on the less hindered side of the styryl radical; in the present case the styryl radical would have bulky groups on all three substituent positions but the fact that benzene entered predominantly on the styryl isomer which would lead to cyclisation suggests that a further molecule of DMAD would behave similarly. No experimental results concerning the phenylbutadienyl radical intermediates are available although the same broad steric considerations probably apply as were applied to the styryl radicals. A fuller mechanistic scheme is now proposed (Scheme 37).



Scheme 37

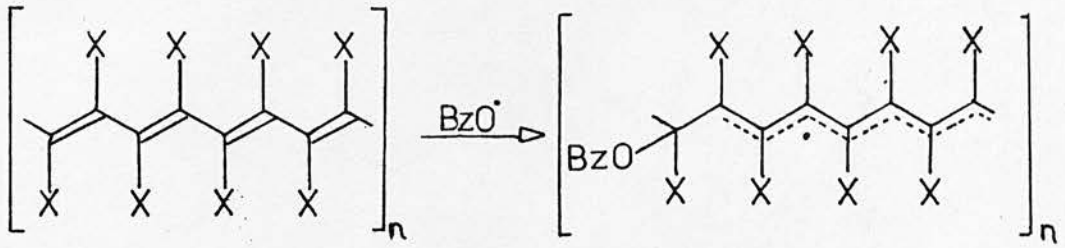
The yields of phenyl radicals and substituted phenyl radicals produced from the corresponding peroxides in DMAD at 80° are very similar using the criterion of carbon dioxide evolution and so the lower yields of naphthalene tetraesters from the substituted phenyl radicals would appear to result from the subsequent addition and cyclisation processes. There is no reason to assume that the initial addition of a substituted phenyl radical to DMAD to give a substituted styryl radical should differ from the addition of a phenyl radical; nor is there any reason why the cis-trans equilibrium of the styryl radical should be affected by a substituent on the phenyl ring. A possible factor acting against addition of a further molecule of DMAD to a styryl radical in the correct cis configuration is steric interference from the ring substituent impeding entry of the DMAD molecule at the angle required for a bond forming transition state.



This would be in keeping with the observation of Singer and Kong[195] that for hydrogen abstraction by styryl radicals the process became increasingly stereoselective as the bulk of the hydrogen donor increased and entry of the donor on the less sterically hindered isomer predominated; in the DMAD case, although its bulk remains constant hindrance to entry cis to the phenyl ring is increased by a substituent on the ring.

The failure to account for around 120 moles aroyloxy radicals per hundred moles diaroyl peroxide in these reactions can be rationalised in terms of trapping of the aroyloxy radicals by the DMAD to give an adduct radical which adds to a further molecule of DMAD, and so on, ultimately to yield a polyene polymer; similarly styryl and phenylbutadienyl radicals not incorporated in cyclised products presumably give rise to polyene polymer systems.

It has been shown by Szwarc[196] that free radicals add more rapidly to a double bond system than to the corresponding triple bond system and so it is probable that any polyenyl polymer produced will itself act as a radical trap, more active per unsaturated unit than DMAD itself (Scheme 38).



Scheme 38

The presence of such a delocalised radical would also explain the absence of any apparent oxidant for the bicyclic radical intermediate formed by the intramolecular cyclisation reaction of phenylbutadienyl radicals, since a delocalised radical would be expected to be much longer lived than aryl or aroyloxy radicals.

In the reaction of dibenzoyl peroxide with DMAD the major shortcoming would appear to be failure of the benzoyloxy radicals to efficiently decarboxylate. Dilution of the system might improve yields by allowing more time for the benzoyloxy radical to decarboxylate and yield a stable phenyl radical, rather than add to the alkyne. The practical difficulty however would be in finding a medium totally inert to attack by any of the radicals in the system. Also assuming that hydrogen abstraction from the bicyclic radical system involves a further radical then there would be a limiting yield of 100 moles naphthalene tetraester per 100 moles peroxide.

The reactions of substituted dibenzoyl peroxides with DMAD suggest that part of the reason for low yields is failure of the substituted benzoyloxy radical to decarboxylate efficiently; the same considerations apply here as applied in the unsubstituted case. Despite similar amounts of phenyl radicals and substituted phenyl radicals being present, far fewer of the substituted radicals are subsequently

identified as being present in the naphthalene tetraester products, the reason for this has not been well established experimentally, although if the reasons are steric it is difficult to see how yields could be improved, as a percentage of the available substituted phenyl radicals.

The Decomposition of Dibenzoyl Peroxide in Phenylacetylene

The measurement of carbon dioxide evolution from the reaction of dibenzoyl peroxide with phenylacetylene indicated that only 16 moles of phenyl radicals per 100 moles of dibenzoyl peroxide were generated and Baigrie[144] found no evidence of these being involved in a cyclisation reaction analogous to that with DMAD. This investigation indicates that the major reactions have been hydrogen abstraction by the benzoyloxy radical to give benzoic acid (90 m/100 m peroxide) and reaction of benzoyloxy radicals (94 m/100 m peroxide) either with phenylacetylene to initiate polymerisation or with the resulting polyene.

The Decomposition of Dibenzoyl Peroxide in Acetonitrile

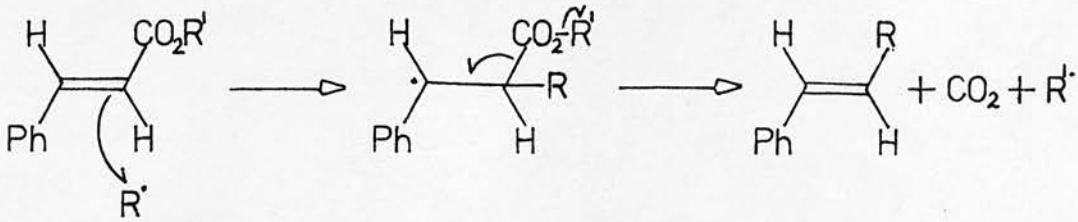
Although the amount of carbon dioxide evolved was not measured in this experiment the isolation of benzoic acid (16 m/100 m peroxide) and biphenyl (5 m/100 m peroxide) and the identification of benzene (39 m/100 m peroxide) indicate that hydrogen abstraction from the methyl group on acetonitrile was the major reaction in this system; no products derived from the cyanomethylene radical were identified and nor were products from the attack of phenyl radicals upon the carbon-nitrogen triple bond.

Attempts to Generate Styryl Radicals by the Decomposition of Dicinnamoyl Peroxides

Attempts to generate unsubstituted styryl radicals by the photolysis of dicinnamoyl peroxide in benzene were unsuccessful using the criterion of stilbene formation; the thermolysis of dicinnamoyl

peroxide in DMAD at 80° similarly failed to show any evidence of styryl radical formation as indicated by the formation of dimethyl-naphthalen-1, 2-dicarboxylate.

The absence of stilbene from the photolysis in benzene is in keeping with the observation of Fieser[197] that styryl derivatives of naphthoquinones could not be obtained from thermolysis of dicinnamoyl peroxide; similarly Hey[178] observed that thermolysis of dicinnamoyl peroxide in benzene only yielded 4 moles stilbene per 100 moles peroxide. The alternative mechanism of induced decomposition, which has been shown to be operative in the reactions of vinyl peroxides[198] may well have been predominant in all of the above cases (Scheme 39).



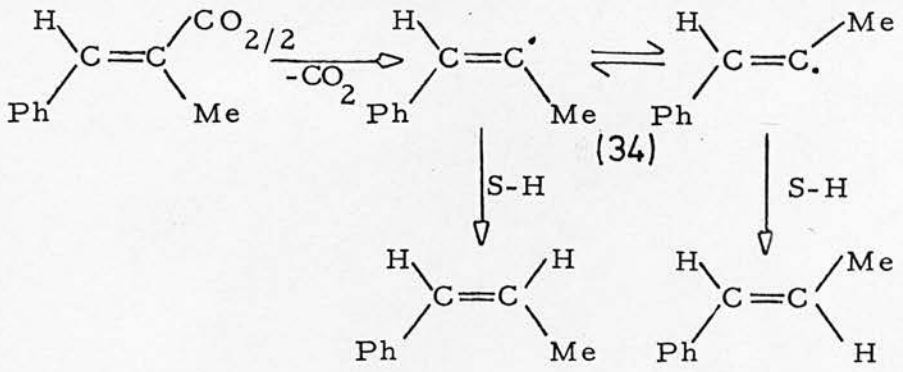
R' = PhCH:CHCO$_2$-

R· = any radical

Scheme 39

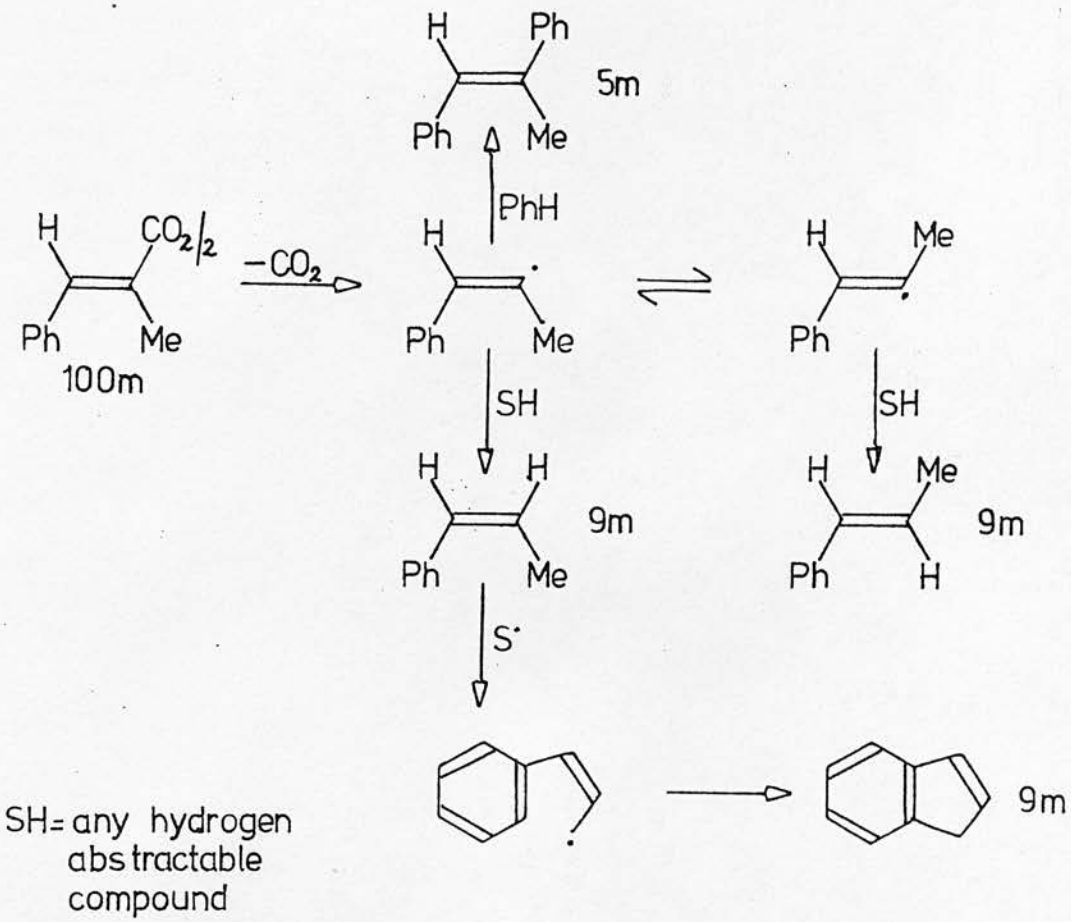
Lead tetraacetate oxidation of cinnamic acid in benzene showed no strong evidence for the presence of free styryl radicals as had been claimed,[199] and the reported isolation of 1-phenylpropene as an addition product of methyl and styryl free radicals[199] could be more credibly rationalised in terms of an induced decomposition mechanism initiated by methyl radicals from the lead tetraacetate (Scheme 39; R=Me, R^1=Pb (IV) $(OAc)_3$).

Bis-α-methylcinnamoyl peroxide has been utilised as a source of the 1-phenylpropen-2-yl radical (34)[195] and at 110° these are known to cis-trans isomerise and hydrogen abstract from hydrogen donor solvents (Scheme 40).



Scheme 40

The decomposition of bis-α-methylcinnamoyl peroxide in benzene gave four products. trans-1, 2-Diphenylpropene was isolated as 5 m/100 m peroxide but none of the cis isomer was observed; this is consistent with entry of the incoming group being on the less hindered conformation of the styryl radical. Similarly cis- and trans-1-phenylpropene and indene, products whose formation can, in part, be rationalised by hydrogen abstraction, predominate in a ratio of 2:1 from hydrogen abstraction on the less hindered side of the equilibrating styryl radical. The proposed mechanism for the decomposition of bis-α-methylcinnamoyl peroxide in benzene is shown (Scheme 41).



Scheme 41

Yields are of finally measured products in m/100 m bis-α-methyl-cinnamoyl peroxide.

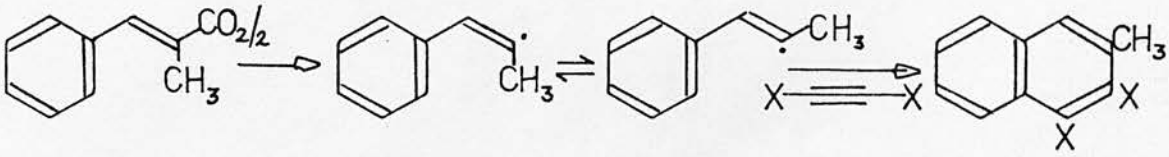
The indene identified could also have been formed by hydrogen abstraction from the peroxide, and cyclisation, prior to fragmentation but the two mechanisms are essentially the same.

The large number of minor products observed by t.l.c. were probably due to subsequent reaction of the double bonds in the styrene and indene products with free radicals.

It was not therefore surprising that the decomposition of bis-α-methylcinnamoyl peroxide in DMAD did not give useful yields of dimethyl 3-methylnaphthalen-1, 2-dicarboxylate since in benzene the hydrogen abstraction reactions presumably involved the peroxide or products derived from it as hydrogen donors, and only the α-methyl stilbene can

be rationalised as a product of attack by a 1-phenylpropen-2-yl radical on the solvent. The DMAD system had a peroxide concentration of approximately 1 mol.l^{-1} (cf 0.1 mol.l^{-1} in benzene) which would increase the probability of hydrogen abstraction reactions; the complexity of products would also have been increased by the observed tendency of styrenes and indenes to undergo Diels-Alder addition with DMAD and other alkynes.[200, 201]

Addition of 1-phenylpropen-yl radicals to DMAD did occur but appears only to have been a minor pathway (Scheme 42).



X= CO_2Me

Scheme 42

The use of most bis-α-alkylcinnamoyl peroxides would have the drawback of being liable to facile free radical hydrogen abstraction from the peroxide and products.

In conclusion it has been shown that styryl free radicals are not generated in any useful quantity from dicinnamoyl peroxide or cinnamic acid and lead tetraacetate, and that the β-methylstyryl radicals generated from bis-α-methylcinnamoyl peroxide will hydrogen abstract from the peroxide and styrene and indene products in preference to addition to benzene or, presumably, DMAD.

References

1 M. Gomberg, Chem. Ber., 1900, 33, 3150.

2 F. Paneth and W. Hofeditz, Chem. Ber., 1929, 62, 1335.

3 W. S. M. Grieve and D. H. Hey, J. Chem. Soc., 1934, 1797.

4 M. S. Kharasch, J. V. Mansfield, and F. R. Mayo, J. Amer. Chem. Soc., 1937, 59, 1155.

5 D. H. Hey and W. A. Waters, Chem. Rev., 1937, 21, 202.

6 (a) Cheeves Walling "Free Radicals in Solution" John Wiley and Sons Inc. New York 1957; (b) "Essays in Free Radical Chemistry," Chem. Soc. Spec. Publ. No. 24, 1970; (c) J. K. Kochi "Free Radicals" Wiley Interscience N. Y., London 1973; (d) D. C. Nonhebel and J. C. Walton "Free Radical Chemistry" Cambridge Univ. Press, 1974.

7 De Los F. De Tar, J. Amer. Chem. Soc., 1967, 89, 4058.

8 A. Rembaum and M. Szwarc, J. Amer. Chem. Soc., 1954, 76, 5975.

9 L. Jaffe, E. J. Prosen and M. Szwarc, J. Chem. Phys., 1957, 27, 416.

10 C. E. Boozer, C. B. Love, J. M. Moles, R. Turner, J. Toney B. G. Moxey, W. N. Christian, and W. W. Stevens, Chem. Abstr., 1963, 59, 2609.

11 L. F. Fieser and F. C. Chang, J. Amer. Chem. Soc., 1942, 64, 2043.

12 D. H. Hey, C. J. M. Stirling, and G. H. Williams, J. Chem. Soc., 1952, 2695.

13 D. H. Hey, C. J. M. Stirling, and G. H. Williams, J. Chem. Soc., 1956, 1475.

14 H. Kolbe, Annalen, 1849, 69, 279.

15 W. A. Waters "The Chemistry of Free Radicals" Clarendon Press, Oxford 1948.

16 P. J. Bunyan and D. H. Hey, J. Chem. Soc., 1960, 3787.

17 W. Braun, L. Rajenbach, and F. R. Eirich, J. Phys. Chem., 1962, 66, 1591.

18 J.C. Bevington and J. Toole, J. Polym. Sci., 1958, 28, 413.

19 R. Hiatt "Organic Peroxides" Vol. II, D. Swern, Wiley-Interscience, 1971.

20 DeLos F. De Tar, R.A.J. Long, J. Rendleman, J. Bradley, and P. Duncan, J. Amer. Chem. Soc., 1967, 89, 4051.

21 W.R. Foster and G.H. Williams, J. Chem. Soc., 1962, 2862.

22 M.T. Jaquiss and M. Szwarc, Nature, 1952, 170, 312.

23 D.H. Hey, J. Chem. Soc., 1934, 1966.

24 Marilyn G. Alder and J.E. Leffler, J. Amer. Chem. Soc., 1954, 76, 1425.

25 H. Zollinger "Diazo and Azo Chemistry" Wiley-Interscience New York, London, 1961.

26 R.L. Hardie and R.H. Thomson, J. Chem. Soc., 1958, 1286.

27 T.W. Campbell, J. Amer. Chem. Soc., 1951, 73, 4019.

28 E. Muller and H. Haiss, Chem. Ber., 1962, 95, 1255.

29 R.G.M. Landells, Ph. D. Thesis, Edinburgh 1976.

30 J.I.G. Cadogan, J. Chem. Soc., 1962, 4257.

31 J.I.G. Cadogan and G.A. Molina, J. Chem. Soc., Perkin I, 1973, 541.

32 M. Gomberg and W.E. Bachmann, J. Amer. Chem. Soc., 1924, 46, 2339.

33 W.S.M. Grieve and D.H. Hey, J. Chem. Soc., 1934, 1797.

34 C. Rüchardt and B. Freudenberg, Tetrahedron Letters, 1964, 3623.

35 S.C. Dickerman, A. Weiss, and A.K. Ingberman, J. Org. Chem., 1956, 21, 380.

36 F.M. Lewis and M.S. Matheson, J. Amer. Chem. Soc., 1949, 71, 747.

37 R.A. Sheldon and J.K. Kochi, J. Amer. Chem. Soc., 1970, 92, 4395.

38 L.M. Dorfman and Z.W. Salsburg, J. Amer. Chem. Soc., 1957, 73, 255.

39 J.M. Blair, D. Bryce-Smith, and B.N. Pengilly, J. Chem. Soc., 1959, 3174.

40 B. Peterson, D. A. G. Walmsley, R. J. Povinelli, and M. Burton, J. Phys. Chem., 1967, 71, 4506.

41 N. A. Milas and D. M. Surgenor, J. Amer. Chem. Soc., 1946, 68, 205.

42 J. Hollaender and W. P. Neumann, Angew. Chem. Internat. Edn., 1970, 9, 804.

43 A. Rembaum and M. Szwarc, J. Amer. Chem. Soc., 1955, 77, 3486.

44 L. Pauling and G. W. Wheland, J. Chem. Phys., 1933, 1, 362.

45 R. H. Porrier, E. S. Khaler, and F. Bennington, J. Org. Chem., 1952, 17, 1437.

46 E. C. Ladd, U. S. Pat. 2,517,684; Chem. Abstr., 1950, 44, 10730.

47 D. D. Tanner and N. J. Bunce, J. Amer. Chem. Soc., 1969, 91, 3028.

48 M. S. Kharasch and W. H. Urry, J. Amer. Chem. Soc., 1944, 66, 1438.

49 R. Pschorr, Chem. Ber., 1896, 29, 496.

50 DeLos F. De Tar and C. Weis, J. Amer. Chem. Soc., 1956, 78, 4296.

51 A. R. Forrester, M. Gill, and R. H. Thomson, J. Chem. Soc. Chem. Comm., 1976, 677.

52 A. L. J. Beckwith and W. B. Gara, J. Amer. Chem. Soc., 1969, 91, 5691.

53 D. L. Struble, A. L. J. Beckwith, and G. E. Gream, Tetrahedron Letters, 1968, 3701.

54 S. A. Kandil and R. E. Dessy, J. Amer. Chem. Soc., 1966, 88, 3027.

55 C. S. Marvel, E. J. Prill, and D. F. De Tar, J. Amer. Chem. Soc., 1947, 69, 52.

56 B. D. Baigrie, J. I. G. Cadogan, J. Cook, and J. T. Sharp, J. C. S. Chem. Comm., 1972, 1318.

57 G. Wittig, Naturwiss, 1942, 30, 696.

58 J. D. Roberts, H. E. Simmons, Jr., L. A. Carlsmith, and C. W. Vaughan, J. Amer. Chem. Soc., 1953, 75, 3290.

59 J. F. Bunnet and R. E. Zahler, Chem. Rev., 1951, 49, 273.

60 R. Huisgen and H. Rist, Naturwiss., 1954, 41, 358.

61 G. Wittig and L. Pohmer, Angew. Chem., 1955, 67, 348.

62 J. I. G. Cadogan, J. K. A. Hall, and J. T. Sharp, J. Chem. Soc. (C), 1967, 1860.

63 A. Luttringhaus and D. Ambros, Chem. Ber., 1956, 89, 463.

64 F. Weggand, A. Schroll, and H. Daniel, Chem. Ber., 1964, 97, 857.

65 V. Franzen, H. I. Joschek, and C. Mertz, Annalen, 1962, 654, 82.

66 J. I. G. Cadogan, A. G. Rowley, J. T. Sharp, B. Sledzinski, and N. H. Wilson, J. C. S. Perkin I, 1975, 1072.

67 D. L. Brydon, J. I. G. Cadogan, D. M. Smith, and J. B. Thomson, J. C. S. Chem. Comm., 1967, 727.

68 E. McNelis, J. Org. Chem., 1963, 28, 3188.

69 F. M. Beringer and S. J. Huang, J. Org. Chem., 1964, 29, 445.

70 M. Stiles and R. G. Miller, J. Amer. Chem. Soc., 1960, 82, 3802.

71 F. M. Logullo, A. H. Seitz, and L. Friedman, Org. Syn., 1968, 48, 12.

72 F. M. Logullo and L. Friedman, J. Amer. Chem. Soc., 1963, 85, 1549.

73 G. Wittig and R. W. Hoffmann, Chem. Ber., 1962, 95, 2718.

74 C. D. Campbell and C. W. Rees, J. Chem. Soc. (C), 1969, 742, 748, 752.

75 M. Keeting, M. E. Peek, C. W. Rees, and R. C. Storr, J. Chem. Soc. Perkin I, 1972, 1415.

76 J. A. Kampmeier and E. Hoffmeister, J. Amer. Chem. Soc., 1962, 84, 3787.

77 G. Wittig and H. F. Ebel, Annalen, 1961, 650, 20.

78 O. L. Chapman, K. Mattes, C. L. McIntosh, J. Pacansky, G. V. Calder, and G. Orr, J. Amer. Chem. Soc., 1973, 95, 6134.

79 O. L. Chapman, C-C. Chang, J. Kolc, N. R. Rosenquist, and H. Tomioka, J. Amer. Chem. Soc., 1975, 97, 6586.

80 H. T. Gruetzmacher and J. Lohman, Annalen, 1967, 705, 81.

81 M. J. S. Dewar and War Kee Li, J. Amer. Chem. Soc., 1974, 96, 5569.

82 I. Tabushi, R. Odo, and K. Okazaki, Tetrahedron Letters, 1968, 3743.

83 R. W. Hoffmann and R. T. Luibrand, J. Org. Chem., 1974, 39, 3887.

84 D. L. Wilhite and J. L. Whitten, J. Amer. Chem. Soc., 1971, 93, 2858.

85 R. Hoffmann, A. Imamura, and W. H. Hehre, J. Amer. Chem. Soc., 1968, 90, 1499.

86 R. Hoffmann and R. B. Woodward, Acc. Chem. Res., 1968, 1, 17.

87 M. Jones, Jr., and R. H. Levin, J. Amer. Chem. Soc., 1969, 91, 6411.

88 C. D. Campbell and C. W. Rees, Proc. Chem. Soc., 1964, 296.

89 L. Friedman, J. Amer. Chem. Soc., 1967, 89, 3071.

90 R. G. Miller and M. Stiles, J. Amer. Chem. Soc., 1963, 85, 1798.

91 M. Stiles and R. G. Miller, J. Amer. Chem. Soc., 1960, 82, 3802.

92 T. L. Gilchrist and C. W. Rees, "Carbenes, Nitrenes and Arynes" Thomas Nelson and Sons Ltd., London, 1969.

93 J. H. Brinkley and L. Friedman, Tetrahedron Letters, 1972, 4141.

94 R. W. Hoffmann "Dehydrobenzene and Cycloalkynes" Academic Press, New York, 1967.

95 B. Andes Hess Jr. and L. J. Schaad, Tetrahedron Letters, 1971, 17.

96 R. Stephen Berry, J. Clardy, and Margaret E. Schafer, Tetrahedron Letters, 1965, 1011.

97 H. E. Bertorello, R. A. Rossi, and Rita Hoyos de Rossi, J. Org. Chem., 1970, 35, 3332.

98 W. N. Washburn, J. Amer. Chem. Soc., 1975, 97, 1615.

99 Alicia H. Amaro and K. Grohmann, J. Amer. Chem. Soc., 1975, 97, 5946.

100 R. S. Berry, J. Clardy, and Margaret E. Schafer, Tetrahedron Letters, 1965, 1003.

101 Rita Hoyos de Rossi, H. E. Bertorello, and R. A. Rossi, J. Org. Chem., 1970, 35, 3328.

102 R. R. Jones and R. G. Bergman, J. Amer. Chem. Soc., 1972, 94, 660.

103 R. Breslow, J. Napierski, and T. C. Clarke, J. Amer. Chem. Soc., 1975, 97, 6275.

104 O. Fischer, Chem. Ber., 1876, 9, 463.

105 H. von Pechmann and L. Frobenius, Chem. Ber., 1894, 27, 651.

106 A. Hantzsch and E. Wechsler, Annalen, 1902, 325, 226.

107 O. Khulung, Chem. Ber., 1896, 29, 165.

108 E. Bamberger, Chem. Ber., 1897, 30, 366.

109 W. S. M. Grieve and D. H. Hey, J. Chem. Soc., 1934, 1797.

110 E. C. Butterworth and D. H. Hey, J. Chem. Soc., 1938, 116.

111 R. Huisgen and G. Horeld, Annalen, 1949, 562, 137.

112 D. H. Hey, J. Stuart-Webb, and G. H. Williams, J. Chem. Soc., 1952, 4657.

113 R. Huisgen, Annalen, 1951, 573, 163.

114 R. Huisgen, Annalen, 1951, 574, 171.

115 R. Huisgen and J. Reinertshofer, Annalen, 1952, 575, 174, 197.

116 D. F. De Tar, J. Amer. Chem. Soc., 1951, 73, 1446.

117 P. Miles and H. Suschitzky, Tetrahedron, 1962, 18, 1369.

118 I. K. Barbon and H. Suschitzky, J. Chem. Soc., 1960, 2735.

119 D. F. De Tar and R. A. J. Long, J. Amer. Chem. Soc., 1958, 80, 4742.

120 G. Binsch and C. Rüchardt, J. Amer. Chem. Soc., 1966, 88, 173.

121 G. Chalfont, M. J. Perkins, D. H. Hey, and K. S. Y. Liang, J. Chem. Soc. Chem. Comm., 1967, 367.

122 G. R. Chalfont and M. J. Perkins, J. Amer. Chem. Soc., 1967, 89, 3054.

123 J. I. G. Cadogan, R. M. Paton, and C. Thomson, J. C. S. Chem. Comm., 1969, 614.

124 J. I. G. Cadogan, R. M. Paton, and C. Thomson, J. C. S. Chem. Comm., 1970, 229.

125 J. I. G. Cadogan, 'Essays in Free Radical Chemistry,' Chem. Soc. Special Publ., No. 24, 1970, 71.

126 J. I. G. Cadogan, D. H. Hey, and G. H. Williams, J. Chem. Soc., 1954, 3352.

127 J. I. G. Cadogan and P. G. Hibbert, Proc. Chem. Soc., 1964, 338.

128 J. I. G. Cadogan, J. Cook, M. J. P. Harger, P. G. Hibbert, and J. T. Sharp, J. Chem. Soc. (B), 1971, 595.

129 D. L. Brydon, J. I. G. Cadogan, J. Cook, M. J. P. Harger, and J. T. Sharp, J. Chem. Soc. (B) 1971, 1996.

130 J. Cook, Ph. D. Thesis, St. Andrews, 1970.

131 B. D. Baigrie, J. I. G. Cadogan, J. Cook, and J. T. Sharp, J. C. S. Chem. Comm., 1972, 1318.

132 C. Rüchardt and C. C. Tan, Angew. Chem. Int. Edn., 1970, 9, 522.

133 P. C. Buxton and H. Heaney, J. C. S. Chem. Comm., 1973, 545.

134 D. V. Banthorpe 'Elimination Reactions' Elsevier Ltd., London, 1963.

135 J. I. G. Cadogan, C. D. Murray, and J. T. Sharp, J. C. S. Perkin I, 1974, 1321.

136 B. D. Baigrie, J. I. G. Cadogan, J. R. Mitchell, A. K. Robertson, and J. T. Sharp, J. C. S. Perkin I, 1972, 2563.

137 P. C. Buxton and H. Heaney, personal communication.

138 J. I. G. Cadogan, C. D. Murray, and J. T. Sharp, J. C. S. Perkin II, 1975, 546.

139 J. R. Mitchell, Ph. D. Thesis, Edinburgh, 1971.

140 V. Hassmann, C. Rüchardt, and C. C. Tan, Tetrahedron Letters, 1971, 3885.

141 C. D. Murray, Ph. D. Thesis, Edinburgh, 1974.

142 J. I. G. Cadogan, C. D. Murray, and J. T. Sharp, J. C. S. Perkin II, 1976, 583.

143 Elizabeth A. Bell, J. I. G. Cadogan, P. W. Milburn, C. D. Murray, R. M. Paton, and J. T. Sharp, J. C. S. Perkin II, 1976, 588.

144 B. D. Baigrie, Ph. D. Thesis, Edinburgh, 1973.

145 B. D. Baigrie, J. I. G. Cadogan, and J. T. Sharp, J. C. S. Perkin I, 1975, 1065.

146 B. Loev and Marjorie M. Goodman, Chem. Ind., 1967, 2026.

147 J. H. Knox, Chem. Ind., 1975, 29.

148 J. J. Kirkland and L. R. Snyder "Introduction to Modern Liquid Chromatography," John Wiley and Sons, New York, 1974.

149 H. France, I. M. Heilbron, and D. H. Hey, J. Chem. Soc., 1940, 369.

150 M. J. P. Harger, Ph. D. Thesis, St. Andrews, 1968.

151 "Dictionary of Organic Compounds," 4th Edition, Eyre and Spottiswoode Ltd., E. and F. Spon Ltd., London, 1965.

152 A. Spassow, Chem. Ber., 1942, 75, 779.

153 M. Gomberg and J. C. Pernet, J. Amer. Chem. Soc., 1926, 48, 1375.

154 A. W. Johnson, J. Chem. Soc., 1946, 895.

155 D. C. Ayres and J. R. Smith, J. Chem. Soc. (C), 1968, 2737.

156 F. D. Chattaway, J. Chem. Soc., 1931, 2495.

157 C. F. H. Allen and F. Converse, Org. Syn., 1926, 6, 32.

158 A. D. Petrov, E. P. Kaplan, and Z. I. Letina, Chem. Abs., 1956 50, 14655.

159 G. W. Cannon, A. Santilli, and Popkin Sherman, J. Amer. Chem. Soc., 1959, 81, 1666.

160 H. H. Schlubach and A. Faltings, Chem. Ber., 1952, 85, 514.

161 J. L. Kice, J. Amer. Chem. Soc., 1958, 80, 350.

162 H. H. Hodgson and R. J. H. Dyson, J. Chem. Soc., 1935, 946.

163 "Organic Reactions" Vol. 5, 193; John Wiley and Sons Inc., New York, 1949.

164 W. S. Saari, U. S. Pat. 3,671, 637; June 20th 1972.

165 K. L. Nelson and H. C. Brown, J. Amer. Chem. Soc., 1951, 73, 5605.

166 A. I. Vogel, "Practical Organic Chemistry," 3rd Edit., Longmans Green and Co. Ltd., London 1959.

167 H. H. Hodgson and C. K. Foster, J. Chem. Soc., 1942, 437.

168 R. Meldola and F. W. Streatfield, J. Chem. Soc., 1888, 53, 676.

169 Niementowski, Chem. Zentralblatt, 1902, 2, 938.

170 E. Bamberger, Chem. Ber., 1903, 36, 2050.

171 H. Hahle, J. Prakt. Chem., 1891, 43, 62.

172 W. Tadros, K. Farahat, and J. M. Robson, J. Chem. Soc., 1949, 439.

173 L. A. Kazitsyna, B. S. Kikof, B. V. Rassadin, and O. A. Reutor, J. Gen. Chem. U. S. S. R., 1963, 33, 221.

174 R. Clinging, F. M. Dean, and G. H. Mitchell, Tetrahedron, 1974, 30, 4065.

175 P. Jacobson, Chem. Ber., 1888, 21, 3104.

176 J. R. Morton and H. W. Wilcox, Inorg. Syn., 1953, 4, 68.

177 W. W. Prichard, Org. Syn., 1948, 28, 68.

178 D. H. Hey and E. W. Walker, J. Chem. Soc., 1948, 2213.

179 A. T. Bloomquist and A. J. Buselli, J. Amer. Chem. Soc., 1951, 73, 3883.

180 D. Swern, "Organic Peroxides," Vol. 2, Wiley Interscience, New York 1971.

181 F. D. Greene and J. Kazan, J. Org. Chem., 1963, 28, 2168.

182 L. A. Singer and L. P. Kong, J. Amer. Chem. Soc., 1966, 88, 5213.

183 "Organic Reactions" Vol. 1, 252, Wiley and Sons, New York, 1942.

184 F. Bergmann, M. Weizmann, E. Dimant, J. Patai, and J. Szmuskowicz, J. Amer. Chem. Soc., 1948, 70, 1612.

185 C. G. Swain, J. E. Sheats, and K. G. Harbinson, J. Amer. Chem. Soc., 1975, 97, 783.

186 C. S. Rondesvedt Jr., and H. S. Blanchard, J. Amer. Chem. Soc., 1955, 77, 1769.

187 R. Huisgen and H. Nakaten, Annalen, 1954, 586, 84.

188 H. D. Hartzler, J. Amer. Chem. Soc., 1964, 86, 2174.

189 M. J. S. Dewar and A. N. James, J. Chem. Soc., 1958, 917.

190 J. K. Stille, P. Cassidy, and L. Plummer, J. Amer. Chem. Soc., 1963, 85, 1318.

191 Chi-Hua Wang, Proc. Chem. Soc., 1961, 309.

192 G. F. Koser and W. H. Pirkle, J. Org. Chem., 1967, 32, 1992.

193 R. Baird and S. Winstein, J. Amer. Chem. Soc., 1963, 85, 567.

194 H. Bohme and H. Schram, Chem. Ber., 1949, 82, 453.

195 L. A. Singer and J. P. Kong, J. Amer. Chem. Soc., 1966, 88, 5213.

196 M. Gazith and M. Szwarc, J. Amer. Chem. Soc., 1957, 79, 3339.

197 L. Fieser and A. E. Oxford, J. Amer. Chem. Soc., 1942, 64, 2060.

198 N. Muramoto, T. Ochiai, O. Simamura, and M. Yoshida, J. C. S. Chem. Comm., 1968, 717.

199 B. Danieli, P. Manitto, F. Ronchetti, and G. Russo, Chem. Ind., 1973, 430.

200 C. Huebner, J. Org. Chem., 1967, 32, 1126.

201 B. F. J. Hudson and R. Robinson, J. Chem. Soc., 1941, 715.

202 R. Tobler, T. Holbro, P. Sutter, and W. Kern, Helv. Chim. Acta, 1941, 24, Engi Festband, 100.